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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01S 3/085, 3/25, 3/025, H01L 33/00

A1

(11) International Publication Number: WO 97/40558

(43) International Publication Date: 30 October 1997 (30.10.97)

(21) International Application Number: PCT/US97/06126

(22) International Filing Date: 14 April 1997 (14.04.97)

(30) Priority Data:
08/635,798 22 April 1996 (22.04.96) US

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(81) Designated States: AL, AM, AT, AU, AZ, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

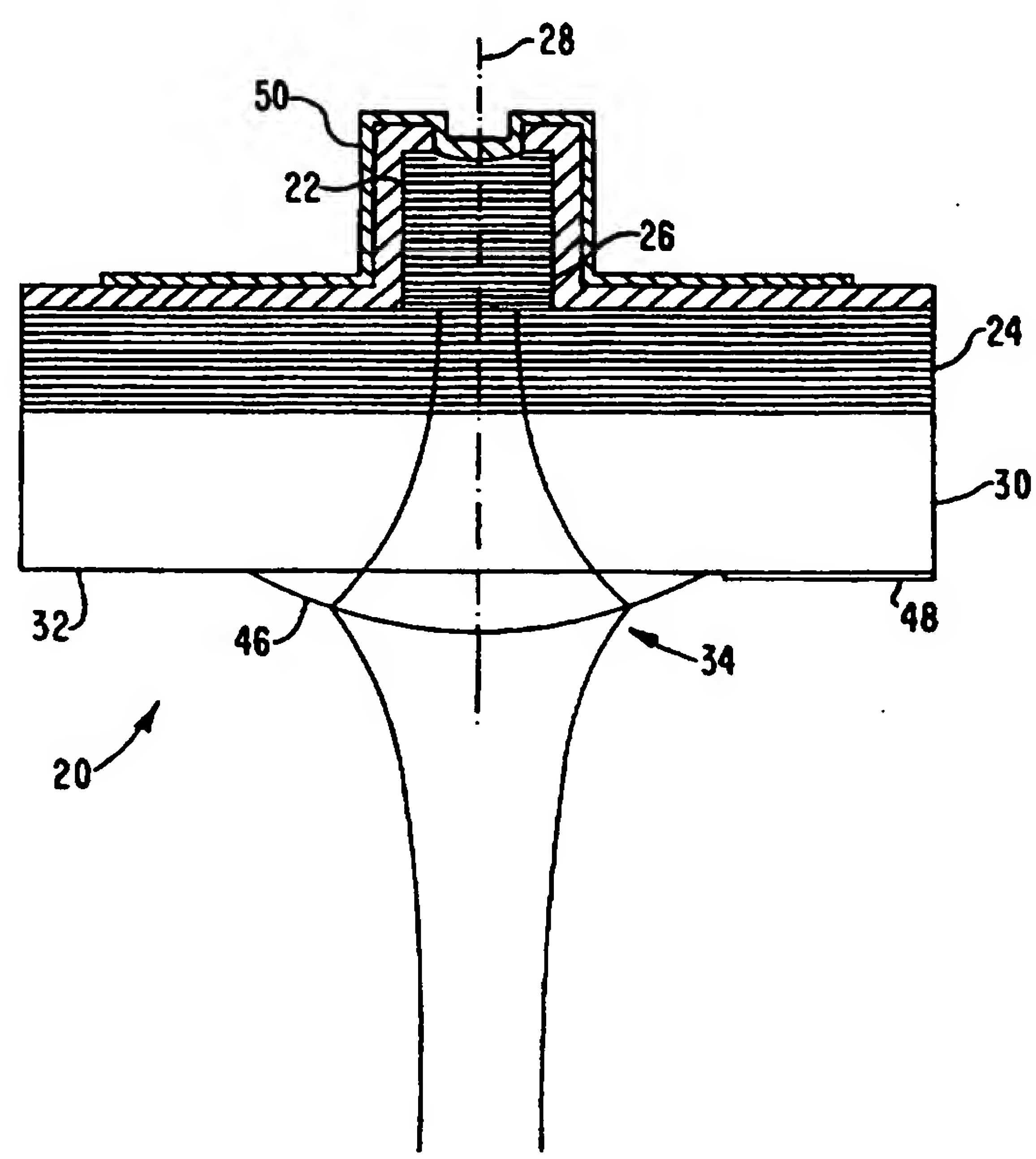
Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: VERTICAL CAVITY LASERS WITH MONOLITHICALLY INTEGRATED REFRACTIVE MICROLENSES

(57) Abstract

Refractive microlenses (34, 38) are monolithically integrated into back-emitting vertical cavity lasers. A back-emitting VCL (20, 36) includes a front mirror, a back mirror being partially transmissive, an optical cavity interposed between the front mirror (22) and the back mirror (24), an active region within the optical cavity (26, 40) between the front and back mirrors, and a substrate (30). The substrate (30, 44) confronts the back mirror (24) and presents a light-emitting back surface (32). A refractive microlens (34, 38) is formed on the back surface (32) of the substrate (30, 44) with a photoresistive polymer or is monolithically integrated into the back surface (32) of the substrate (30, 44) using the photoresistive polymer. In microlens processing, poly(dimethylgluterimide) (PMGI), a deep ultraviolet photoresist is spin-coated on the polished back surface (32) of the substrate (30, 44) containing the fabricated VCL (20, 36). An imaging layer of conventional positive photoresist is spin-coated and patterned on the VCL. The PMGI is exposed to deep ultraviolet light using the patterned positive photoresist as a portable conformal mask. The exposed PMGI is then developed away and the positive photoresist is removed using acetone. The resultant structure is a cylinder of PMGI. A thin layer of the substrate around the PMGI cylinder is recessed. The PMGI cylinder is reflowed at 300 °C for 5-15 minutes. A parabolic lens shape of reflowed PMGI is obtained and is transferred to the substrate (30, 44) using reactive ion etching.



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VERTICAL CAVITY LASERS WITH MONOLITHICALLY INTEGRATED REFRACTIVE MICROLENSES

FIELD OF THE INVENTION

This invention relates generally to vertical cavity lasers; and, more particularly to back-emitting vertical cavity lasers with monolithically integrated refractory microlenses.

BACKGROUND OF THE INVENTION

A vertical cavity laser (VCL) is a semiconductor laser consisting of a semiconductor layer of optically active material, such as gallium arsenide or indium gallium arsenide, sandwiched between highly-reflective layers of metallic material, dielectric material, epitaxially-grown semiconductor material or combinations thereof, the layers forming mirrors. Conventionally, one of the mirrors is partially reflective so as to pass a portion of the coherent light built up in the resonating cavity formed by the mirror/active layer sandwich. Laser structures require optical confinement and carrier confinement to achieve efficient conversion of pumping electrons to stimulated photons (a semiconductor may lase if it achieves population inversion in the energy bands of the active material). The standing wave in the cavity has a characteristic cross-section giving rise to an electromagnetic mode. A desirable electromagnetic mode is the single fundamental mode, for example, the HE_{11} mode of a cylindrical waveguide. A single mode signal

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from a VCL is easily coupled into an optical fiber, has low divergence and is inherently single frequency in operation.

An important commercial application of vertical-cavity lasers is in both guided wave and free space computer interconnections. Previous practice requires expensive and time consuming active alignment techniques requiring micro-machined features and precision micro-manipulators for mounting discrete focusing and beam collimating discrete components. A need continues for better beam focusing and beam collimating techniques, particularly for guided wave and free space computer interconnections.

SUMMARY OF THE INVENTION

Better laser beam focussing and laser beam collimating capability for vertical cavity lasers and optical detectors can be achieved by monolithically integrating refractory microlenses into back-emitting vertical cavity lasers (VCLs) and optical detectors in accordance with the principles of the invention. Such a back-emitting VCL includes a front mirror, a back mirror, an optical cavity interposed between the front and back mirrors, an active region within the optical cavity, and a substrate. The substrate confronts the back mirror and presents a light-emitting back surface. A refractory microlens is formed on the back surface of the substrate with a photoresistive polymer, or is monolithically integrated into the back surface of the substrate

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using the photoresistive polymer in a reactive ion etching process. Monolithic integration of refractory microlenses into VCLs eliminates the cumbersome alignment processes of previous practice because fabrication of the lens is part of the VCL processing procedure. Microlenses fabricated into the back lens surface of back-emitting VCLs have a high refractory index (matching that of the substrate from which they are made). This enables high numerical aperture (NA) lenses to be produced.

Arrays of VCLs with associated arrays of integral microlenses can be fabricated. By controlling the spacing of the microlenses with respect to the spacing of the VCLs in the respective arrays, emitted laser beams can be made to diverge in travel toward an optical detector, or can be made to converge to one point of the optical detector.

In an illustrative embodiment, integrated microlens fabrication includes reflowing (i.e., controlled melting), of photoresist into a microlens having a parabolic cross-section. This microlens is transferred, using reactive ion etching (RIE), to the backside of a III-V compound (e.g., gallium arsenide (GaAs) or indium phosphide (InP)) semiconductor substrate of a back-emitting VCL.

Poly(dimethylgluterimide) ("PMGI"), a deep ultraviolet (UV) photoresist, is used as a sacrificial mask. PMGI is spin coated on the polished backside of the substrate(s) containing the fabricated VCL(s); it should be noted that many VCLs or

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optical detectors can be manufactured in a wafer substrate. An imaging layer of conventional positive photoresist is spin coated on the VCL substrate. The conventional positive photoresist is patterned using an infrared (IR) mask aligner to precisely align (to a tolerance of <1 micron) the lens center to the central vertical axis of the VCL. The PMGI beneath the patterned positive photoresist is exposed to deep UV using the patterned positive photoresist as a portable conformal mask (PCM) that is opaque to deep UV radiation.

The exposed PMGI is then developed away and the positive photoresist is removed using acetone. The resultant structure is a cylinder of PMGI. The thickness and diameter of the cylinder of PMGI can be controlled to less than 1 micron.

A thin layer of the substrate (< 0.5 micron) around the PMGI cylinder is recessed with a solution of $H_3PO_4:H_2O_2:H_2O$ (1:5:50). This results in lithographically defined PMGI cylinders on GaAs pedestals. The GaAs pedestals constrain by surface tension the PMGI during reflow (melting) to a fixed diameter.

The PMGI cylinders are reflowed at a temperature of 300°C for 5-15 minutes, depending on the thickness of the PMGI. Near-parabolic cross-sectional shapes of reflowed PMGI are obtained.

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This near-parabolic cross-sectional shape is transferred to the VCL substrate using reactive ion etching (RIE). The RIE stage uses Cl_2 typically at 1 mT and 350 Vdc (power 60W) bias in a parallel plate chamber. Transferring the shape integrates a microlens into the VCL substrate.

The radius of curvature in a cross-section of the created microlens can be modified in the RIE stage by adjusting the etch conditions to change the relative etch rates of PMGI and the semiconductor substrate. By varying (a) the initial PMGI thickness, (b) diameter, and (c) relative etch rate, microlenses having a numerical aperture (NA) of up to 0.4 and focal lengths from 10 to 1000 microns can be achieved. After lens fabrication, the back surface can be covered with a silicon oxide (SiO) anti-reflection coating to minimize optical feedback.

A similar technique for monolithically integrating microlenses into indium phosphide (InP)-based substrates employs different etchant chemicals and etching rates. The similar technique is also applicable to GaAs-based substrates.

Other features and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawing, which illustrate, by way of example, the features of the invention.

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BRIEF DESCRIPTION OF THE DRAWING

In the drawing:

FIG. 1 shows a refractory microlens formed on a back-emitting VCL;

FIG. 2 shows a back-emitting VCL having two substrate layers and a monolithically integrated refractory microlens;

FIG. 3 shows a back-emitting VCL array with integrated microlenses focussing into a fiber array;

FIG. 4 shows a back-emitting VCL array with a convergent microlens arrangement;

FIG. 5 shows a back-emitting VCL array with a divergent microlens arrangement;

FIGS. 6-13 schematically present a process for fabricating integrated microlenses; and

FIG. 14 shows a hermetically-sealed package for VCLs with integrated microlenses for free-space applications.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

According to the principles of the invention, back-emitting vertical cavity lasers (VCLs) or optical detectors are integrated with refractive microlenses. A back-emitting VCL 20 includes a front mirror 22, a back mirror 24, an optical cavity 26, which includes an active region, interposed between the front mirror 22 and the back mirror 24 having a central vertical axis 28, and a substrate 30 confronting the back mirror and presenting

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a light-emitting back surface 32. A refractory microlens 34 is disposed on the back surface 32.

The front mirror 22 and the back mirror 24 each include a stack of alternating layers of AlGaAs and GaAs. The optical cavity 26 includes InGaAs as the active medium. The substrate 30 includes one or more semiconductor layers selected from the group consisting of GaAs, InP, and combinations thereof.

FIG. 2 shows a back-emitting VCL 36 having two semiconductor layers monolithically integrated with a refractory microlens 38. The VCL 36 includes an optical cavity 40 consisting of an InGaAs active medium in confronting relationship with an InP substrate layer 42. The InP substrate layer 42 is wafer-fused to a GaAs substrate layer 44. The refractory microlens 38 is monolithically integrated directly into the GaAs substrate layer 44.

The refractory microlens 34 (FIG. 1) can consist of a photosensitive polymer such as poly(dimethylgluterimide), denoted "PMGI" in the art, or the refractory microlens 34 can be monolithically integrated into the substrate 30 of the back-emitting VCL 20. An optional anti-reflection coating 46 can be formed on the refractory microlens 34.

An n-type electrode 48 and a p-type electrode 50 are applied to the VCL 20 so that the VCL 20 can be electrically pumped. The p-type electrode 50 is fabricated from AuZnAu and

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applied to the front mirror 22. The n-type electrode 48 is fabricated from CrAu and applied to the substrate 30.

Refractive microlenses are etched on the back side of VCL semiconductor substrates in a wafer-scale fabrication process according to the principles of the invention. This fabrication process enables arrays of refractory microlenses to be combined and juxtaposed with arrays of back-emitting VCLs created in a substrate wafer.

FIG. 3 shows an array 52 of back-emitting VCLs formed on a substrate wafer 54. An array 56 of refractory microlenses is formed on the substrate wafer. The array of microlenses can be formed of a photoresistive polymer such as PMGI, or can be monolithically integrated directly into the substrate wafer for free-space interconnections. When such a VCL array is driven to emit laser light, the array of microlenses can be used to collimate and focus the emitted laser light 58 toward a target, such as an optical detector or an optical detector array 60. The center 62 of the refractory microlens surface can be aligned with the central vertical axis 64 of the optical cavity, as shown in FIG. 3, to focus or collimate the individual laser beams. The center 62 can also be displaced from the central vertical axis to focus multiple laser beams in a single spot, as shown in FIG. 4, or to spread out the laser beams as shown in FIG. 5.

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The spacing between microlenses in an array of microlenses can be varied with respect to the spacing of VCLs in an array of VCLs using a photolithographic mask to support a convergent laser light emission pattern (FIG. 4) or a divergent laser light emission pattern (FIG. 5).

In the convergent laser light emission pattern shown in FIG. 4, the light from all the VCLs converge on the same point. The center of each microlens is displaced from the central vertical axis of its associated VCL by an offset. For the middle VCL 66 of the VCL array 68 the offset between the center of its associated microlens 70 and the central vertical axis 72 of the VCL 66 is zero. The middle VCL 66 and its associated microlens 70 are aligned with a receiving point 74 of an optical detector 76. Other microlenses on either side of the middle microlens 70 are offset from their associated VCLs so that the emitted laser light converges on the receiving point 74. For a microlens associated with a VCL, the offset in the direction toward the middle microlens 70 increases with the distance of the VCL from the middle VCL 66. This offset spacing of the microlenses with respect to the spacing of the VCLs causes emitted laser light focussed by each microlens to converge to the receiving point 74 in travel toward the optical detector array 76. By selectively positioning the optical detector array linearly from the microlens array 77, converging laser beams from the VCL array can be combined at the receiving point. This can be useful for

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increasing power output required for a particular application. For example, the output laser emissions from ten 5 mW VCLs in an array can be converged to provide 50 mW of power to the receiving point.

In the divergent laser light emission pattern shown in FIG. 5, the spacing between microlenses causes emitted laser light focussed by each microlens to diverge in travel toward an optical detector array. The center of each microlens is displaced from the central vertical axis of its associated VCL by an offset. The offset of the middle microlens 78 with respect to the associated middle VCL 79 is zero. The middle VCL 79 and its associated middle microlens 78 are aligned with a middle optical detector 80 of the optical detector array 82.

Microlenses on either side of the middle microlens 78 are offset from their associated VCLs so that the emitted laser beams diverge in travel toward the detector array 82. For a microlens associated with a VCL, the offset between the microlens and the associated VCL in the direction away from the middle microlens 78 increases with the distance of the VCL from the middle VCL 79. This accommodates various spacing between optical detectors in the detector array 82.

Monolithically integrating microlenses into the back surface of back-emitting VCLs enhances laser beam focusing and collimation for the VCLs. This achievement greatly simplifies free space and/or fiber alignment packaging and testing of VCLs.

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These steps are repeated until the desired thickness is achieved. Typically a total thickness of 6 microns is pre-selected and used to achieve a lens with the desired radius of curvature for a 200 micron diameter lens in GaAs.

The target thickness of PMGI is easily achieved by applying two coats of PMGI with controlled spin speeds. For example, the first layer is spun at 3500 RPM for a 3 micron thickness, which is followed by a second layer of PMGI spun at 4500 RPM for a total thickness of 5 microns.

Various viscosities of PMGI may also be used for finely tuned control of thickness.

Precision tailoring of the thickness can also be achieved by etching the PMGI 84 in an oxygen plasma using a conventional parallel plate plasma reactor. This procedure is rarely required since the controlled spin speeds recited herein produce PMGI thicknesses well within the tolerances required to achieve the desired lens shape.

The selected thickness of the PMGI 84 is based on the diameter and radius of curvature desired for the resultant GaAs lens. When the relative etch rates of the PMGI and the GaAs have been determined for controllable etching parameters for a given reactive ion etcher, consistent results are easily obtained.

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A conventional positive resist 88, e.g., *AZ1420, Hoechst Celanese Corp., Somerville, NJ,* or an equivalent, is applied onto the PMGI coating 84. The positive resist coating 88 is spun at 4000 ±100 RPM for 30 ±5 sec. The positive resist coating 88 is baked on a hot plate for 30 ±5 sec. at 90 ±5°C.

A photolithographic contact mask aligner with infrared (IR) viewing capability, e.g., *Karl Suss MJB3-IR, Waterbury Center, VT,* presents a light field photolithographic mask containing desired patterns. The light field photolithographic mask is aligned to the laser or optical detector. The IR mask aligner permits observation of the VCLs or optical detectors through the substrate permitting precise alignment to tolerances of 1 micron or better.

Referring to FIG. 7, the positive resist coating 88 is exposed to UV light, typically 7.5 mW/cm^2 at a wavelength of 405 nm for 15 sec. The exposed positive resist 88 is developed using an appropriate developer, e.g., Hoechst AZ 4000, or equivalent. The developed positive resist 88 has a pattern that corresponds to the light field photolithographic mask and acts as a portable conformal mask (PCM) for defining the PMGI.

The resist coated substrate 86 is flood-exposed with deep ultraviolet light using a deep ultraviolet light source, e.g., *OAI (Optical Associates, Inc.), Milipitas, CA* or *Fusion Semiconductor Systems, Rockville, MD,* or an equivalent. Flood exposure is typically at 10 mW/cm^2 for 5 min. at 457 nm wave-

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length. The exposed PMGI 84 is developed in *Shipley SAL 101, Shipley Co., Newton, MA,* or an equivalent, developer for 2 min. ±10 sec.

The positive resist pattern is opaque to deep ultraviolet light and permits deep ultraviolet radiation of the PMGI 84 only in the areas 90 clear of the positive resist. Exposure and development times depend upon the power of the deep ultraviolet light of the source used.

Flood exposure of the resist coated substrate 86 can be repeated, if required, until the PMGI 84 is removed in the areas 90 not covered by the positive resist 88.

The positive resist 88 is then removed by applying acetone. The acetone does not attack the PMGI 84. Such acetone application results in a cylinder of PMGI 84, as shown in FIG. 8. The diameter and thickness of the cylinder of PMGI 84 is precisely defined and aligned to the VCL 92 or detector.

Referring to FIG. 9, a layer 94 of positive photoresist is then applied to the device side of the substrate 86. The positive photoresist layer 94 is cured on a hot plate at 90°C for 1-2 min. This step is done to protect the devices during the following step.

A solution for etching GaAs, consisting of phosphoric acid/hydrogen peroxide/water, $H_3PO_4:H_2O_2:H_2O$ (1:5:50), is prepared. The exposed GaAs substrate 86 circumscribing the PMGI cylinder 84 is etched in the prepared etch solution for 15 ±2 sec. to remove

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a thin layer of the GaAs (~0.5 micron). The area is rinsed with deionized water (DI H_2O) and blow-dried with dry nitrogen. This leaves the PMGI cylinders 84 on GaAs pedestals 96 (shown in FIG. 10) which constrain, by surface tension, the PMGI 84 during reflow to a fixed diameter. The positive resist 94 is removed by applying acetone. Such application is followed with an isopropyl alcohol (IPA) rinse and blown dry.

The substrate 86 and PMGI cylinder 84 on the pedestal 96 are placed in an oven filled with nitrogen. The temperature of the oven is made to be above the glass transition temperature of the PMGI, which is about ~197°C. The oven temperature is typically in the range of 290-300°C, and heating to reflow the PMGI is for 5 to 30 minutes, depending upon the PMGI thickness.

Optionally, the shape of the reflowed PMGI can be confirmed using a surface profilometer. If the profile is not optimum, an additional reflow may be performed or the profile can be modified using an oxygen plasma as described previously. This is rarely required because of the precision obtained using these process steps. Referring to FIGS. 11 and 12, a PMGI microlens 84 formed at this stage of the process can be used as a collimating or focusing lens.

Numerous parallel plate reactive ion etching (RIE) systems are commercially available for reactive ion etching. A parallel plate RIE system is used to transfer the lens formed in the reflowed PMGI 84 into the GaAs substrate 86 to create a

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monolithically integrated microlens 98 in the substrate 86, as shown in FIG. 13.

Various etching gases (e.g., borontrichloride (BCl_3), silicontetrachloride ($SiCl_4$) and chlorine (Cl_2)) can be optimized in various combinations to produce superior quality microlenses, depending upon the plasma etcher configuration and etching parameters (e.g., gas flow, chamber pressure, bias voltage, etc.) of a particular RIE system.

In the first embodiment, the RIE system incorporates a vertical parallel plate configuration and uses Cl_2 etchant gas.

The substrate is placed, device side down, using a low vapor pressure, thermally conductive adhesive, e.g., Mung, to attach the substrate to the cathode plate of the vertical parallel plate configuration. A test sample with PMGI, of thickness equaling that of the reflowed PMGI, is also placed on the cathode plate to be used as an etch monitor.

The RIE system incorporates a load-lock for evacuation of the cathode with the mounted substrate and the etch monitor to permit insertion into the main chamber which is under high vacuum. This is not a necessary requirement, but is useful since the main chamber does not have to be vented to atmosphere to load the substrate. Most commercially available RIE systems provide a load-lock as an option.

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Typical etching parameters of the RIE system used are: Cl_2 at 7.5 sccm (standard cubic centimeters/min.), pressure at 1 mT (milliTorr), 350 V d.c. bias at 60 watts. A typical etch rate of the PMGI is 1200 angstroms/min. The etching of the PMGI is monitored by directing the light emitted from a helium\neon (HeNe) laser through an optical port in the RIE chamber onto the PMGI test sample for etch monitoring. The reflected light from the PMGI test sample is directed into a silicon photodetector. The output of the silicon photodetector is used to drive an X-Y recorder. The output of the detector results in a sinusoidal display on the chart recorder due to the interference as a function of the thickness of the PMGI. The periods of the sinusoidal patterns are 1/4 wavelength of the HeNe laser (1530 angstroms). By knowing the precise etch rate of the PMGI, which is related to the predetermined etch rate of the GaAs, the etching process can be terminated at the proper time to prevent excessive etching of the GaAs.

Following the etching process the substrate is removed from the RIE chamber. The substrate is rinsed with deionized water to remove any residual Cl_2. Removing the mounting adhesive with acetone or IPA completes microlens 98 (FIG. 13) fabrication.

Following fabrication of a microlens, an optional SiO anti-reflection coating can be deposited on the lens side of the substrate to prevent light reflection into the VCL or optical detector.

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Back-emitting GaAs/AlGaAs VCLs with extremely minimal far-field beam divergence can be fabricated according to the procedure taught herein. VCLs having a single mode in the transverse direction were fabricated and operated up to their peak power levels. Their beam profile was measured by scanning a detector with a 50 micron diameter pinhole across the beam. Without a lens, the divergence angle of beams from a 7 micron diameter device was 6.5°. With a lens the divergence was decreased to achieve a near-collimation condition. The divergence angles were 2.2 and 1.9° with lenses of radii of curvature of 560 and 316 microns, respectively.

In a second microlens processing embodiment of the invention, refractory microlenses can be made integral with indium phosphide (InP)-based substrates in VCLs and optical detectors. The procedure for fabricating microlenses in indium phosphide (InP) is the same as the gallium arsenide (GaAs) procedure taught herein with the exception of the etching system and gases used.

To fabricate the microlenses into an InP substrate, a Plasma-Therm parallel plate reactive ion etcher (RIE) is used. The etching gasses are: brominetrichloride:silicontetra-chloride:chlorine, $BrCl_3$:$SiCl_4$:Cl_2, 25 standard cubic centimeters/minute (sccm):5sccm:2sccm at a pressure of 10 milliTorr (mT). By adjusting the RF power and the pressure, the relative etch rates of the InP and the PMGI can be controlled.

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This is important for controlling the shape of the resultant lens and eases photolithographic requirements.

The second processing embodiment for integrating microlenses into InP-based substrates works for GaAs-based substrates with only slight changes in the etching parameters. This procedure significantly enhances the microlens integrating process and ensures that manufacturing viability can be realized.

It is contemplated that a VCL 100 (or VCL array) with integrated microlens(es) can be hermetically sealed in a commercial package 102, as shown in FIG. 14. The commercial package 102 can include driver and receiver circuitry 104 for free-space communications. The commercial package 102 shown in FIG. 14 presents an anti-reflection coated window 106 (e.g., made of sapphire) which passes an outgoing collimated laser beam 108 while preventing optical feedback into the package 102.

While several particular forms of the invention have been illustrated and described, it will also be apparent that various modifications can be made without departing from the spirit and scope of the invention.

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WHAT IS CLAIMED IS:

1. An optically focussed back-emitting vertical cavity laser (VCL), comprising:

a front mirror;

a back mirror being partially transmissive;

an optical cavity interposed between said front mirror and said back mirror and having a central vertical axis;

an active region within said optical cavity between said front mirror and said back mirror;

a substrate confronting said back mirror and presenting a back surface; and

a refractory microlens disposed on said back surface.

2. The back-emitting VCL of claim 1, wherein:

the center of the microlens is aligned with said central vertical axis.

3. The back-emitting VCL of claim 1, wherein:

the center of the microlens is displaced from said central vertical axis.

4. The back-emitting VCL of claim 1, wherein:

said substrate comprises a compound semiconductor selected from the group consisting of gallium arsenide and indium phosphide.

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5. The back-emitting VCL of claim 1, further comprising:

an anti-reflection coating formed on said refractory microlens.

6. The back-emitting VCL of claim 1, wherein:

said refractory microlens includes PMGI.

7. The back-emitting VCL of claim 1, wherein:

said refractory microlens is integral with said back surface.

8. The back-emitting VCL of claim 1, further comprising:

a p-type electrode applied to said front mirror; and

an n-type electrode applied to said substrate.

9. The back-emitting VCL of claim 1, wherein:

said substrate is an n-type substrate.

10. A method of integrating a refractory microlens into a back-emitting vertical cavity laser (VCL) having a central vertical axis and including a substrate which presents a back surface, comprising the following steps:

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(A) coating PMGI on the back surface of the substrate;

(B) forming a portable conformal mask on the PMGI which is positioned with respect to the central vertical axis of the VCL;

(C) removing the PMGI exposed by the portable conformal mask;

(D) removing the portable conformal mask to form a PMGI cylinder;

(E) recessing a section of the substrate circumscribing the PMGI cylinder; and

(F) reflowing the PMGI cylinder into a microlens.

11. The method of claim 10, further comprising the step:

transferring the microlens using reactive ion etching into the back surface of the substrate.

12. The method of claim 11, further comprising the step:

etching the PMGI cylinder and the substrate with chlorine.

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13. The method of claim 10, wherein:

the substrate comprises a compound semiconductor selected from the group consisting of gallium arsenide and indium phosphide.

14. The method of claim 10, wherein step (B) includes the steps:

spin coating an imaging layer of conventional positive photoresist on the PMGI; and

patterning the imaging layer to form the portable conformal mask.

15. The method of claim 10, wherein step (C) includes the steps:

exposing the PMGI to deep ultraviolet radiation; and

developing the exposed PMGI.

16. The method of claim 10, further comprising the step:

polishing the back surface of the substrate before coating the PMGI.

17. The method of claim 10, wherein:

in step (F), the PMGI is reflowed at approximately 300 °C for a duration in the range of 5 to 15 minutes.

BNSDOCID: <WO_______9740558A1_I_>

18. The method of claim 10, wherein:

the microlens has a parabolic cross-sectional configuration.

19. A method of integrating a refractory microlens into a back-emitting vertical cavity laser (VCL) having a central vertical axis and including a substrate which presents a back surface, comprising the following steps:

(A) applying a PMGI coating onto the back surface of the substrate;

(B) applying a patterned positive resist coating defining a light field photolithographic mask to the PMGI coating;

(C) aligning the patterned positive resist coating and the central vertical axis;

(D) developing the patterned positive resist coating;

(E) flood exposing the patterned positive resist coating with deep ultraviolet light to remove the PMGI in the areas exposed by the patterned positive resist coating;

(F) removing the patterned positive resist coating to form a PMGI cylinder;

(G) etching a section of the substrate circumscribing the PMGI cylinder to dispose the PMGI cylinder on a substrate pedestal;

BNSDOCID: <WO_________9740558A1_I_>

(H) heating the substrate and the PMGI cylinder in a nitrogen atmosphere to reflow the PMGI cylinder into a microlens; and

(I) reactive ion etching the microlens with an etchant gas to transfer the microlens into the substrate.

20. The method of claim 19, further comprising the step:

repeating step (A) to achieve a preselected coating thickness of PMGI.

21. The method of claim 19, wherein step (D) includes the step:

exposing the positive resist coating to ultraviolet light.

22. The method of claim 19, further comprising the step:

repeating step (E) until the PMGI is removed in the areas exposed by the positive resist coating.

23. The method of claim 19, wherein:

the etchant gas in step (I) is chlorine.

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24. The method of claim 19, wherein:

the substrate comprises a compound semiconductor selected from the group consisting of gallium arsenide and indium phosphide.

25. The method of claim 19, further comprising the step:

disposing the back-emitting VCL in a hermetically-sealed package, which includes circuitry for free-space communication applications.

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FIG. 1

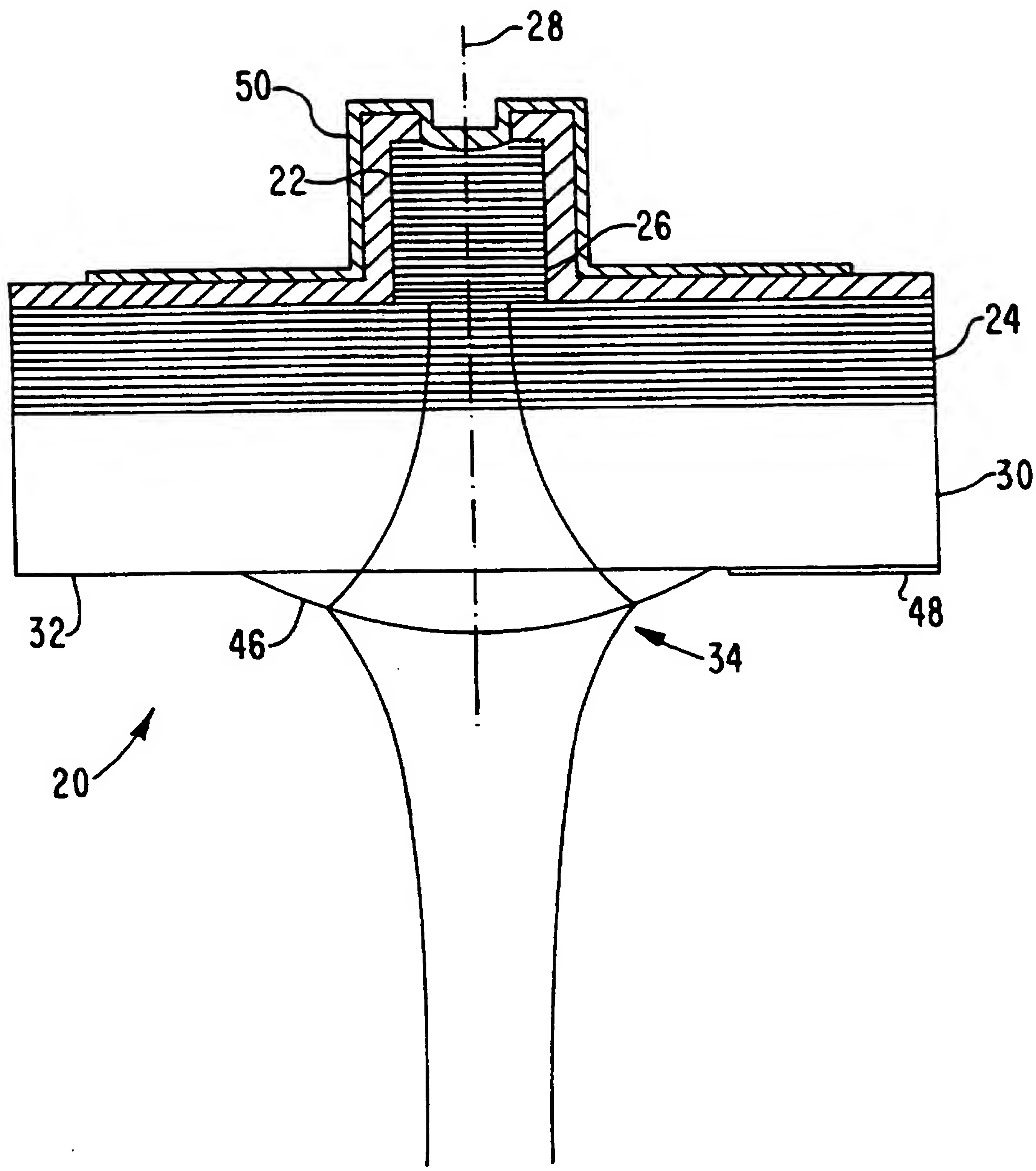


FIG. 2

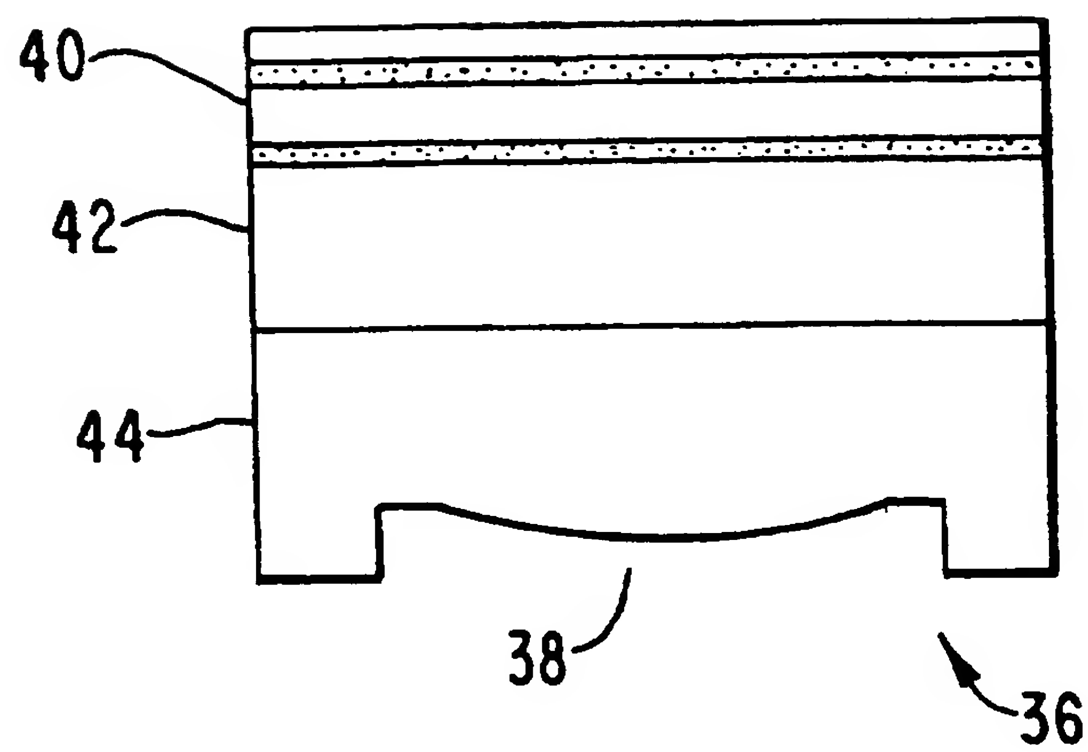


FIG. 3

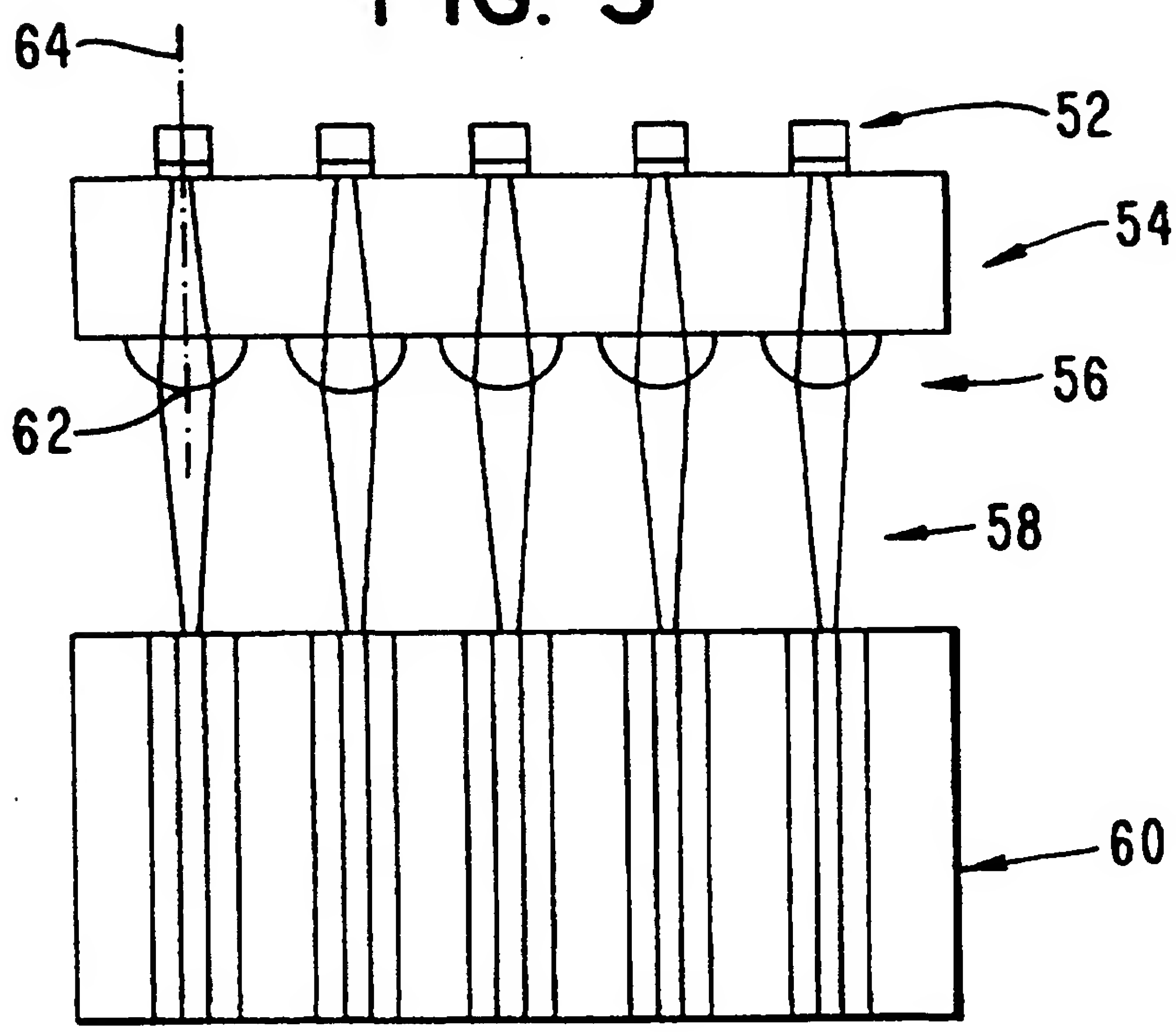
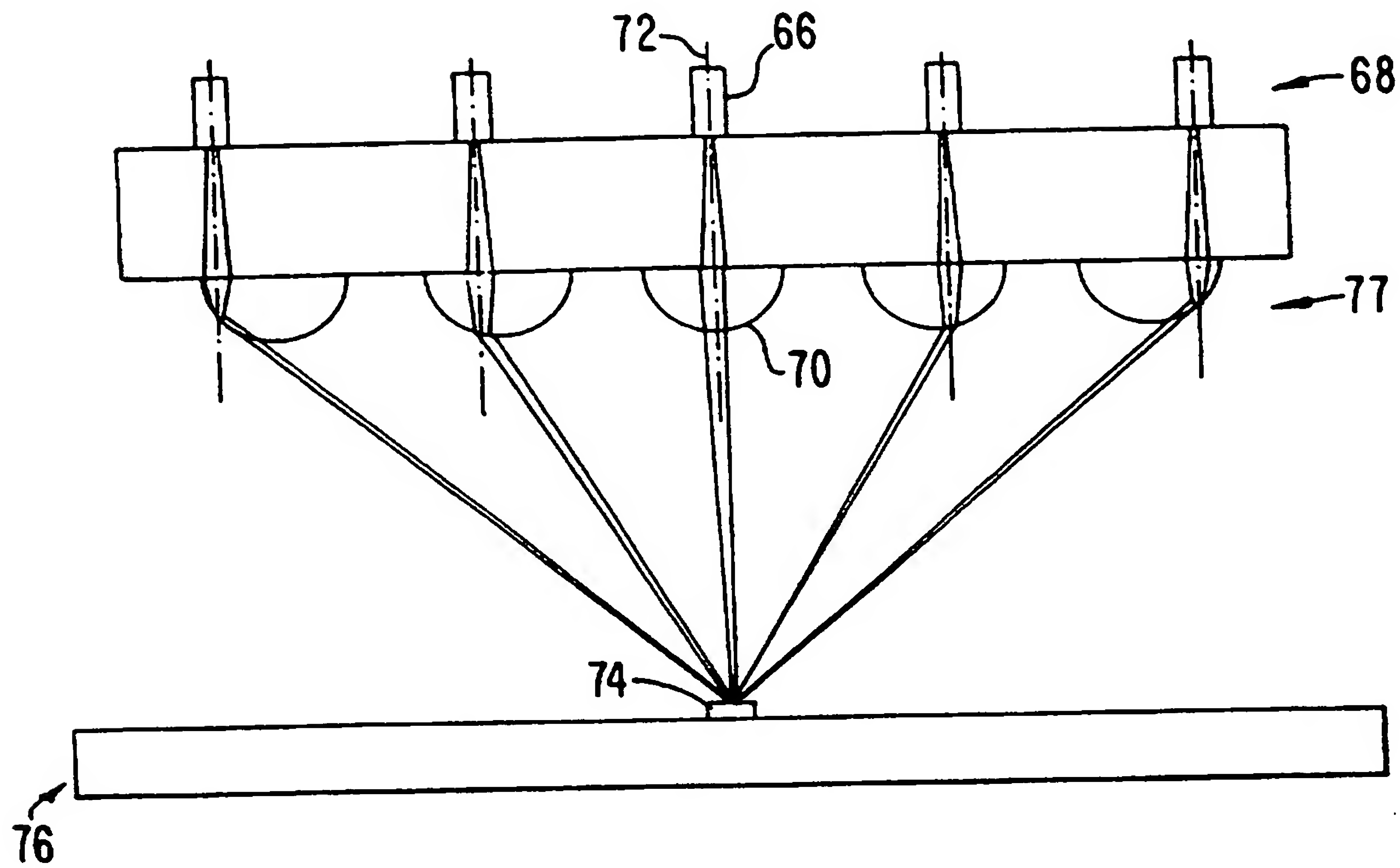


FIG. 4



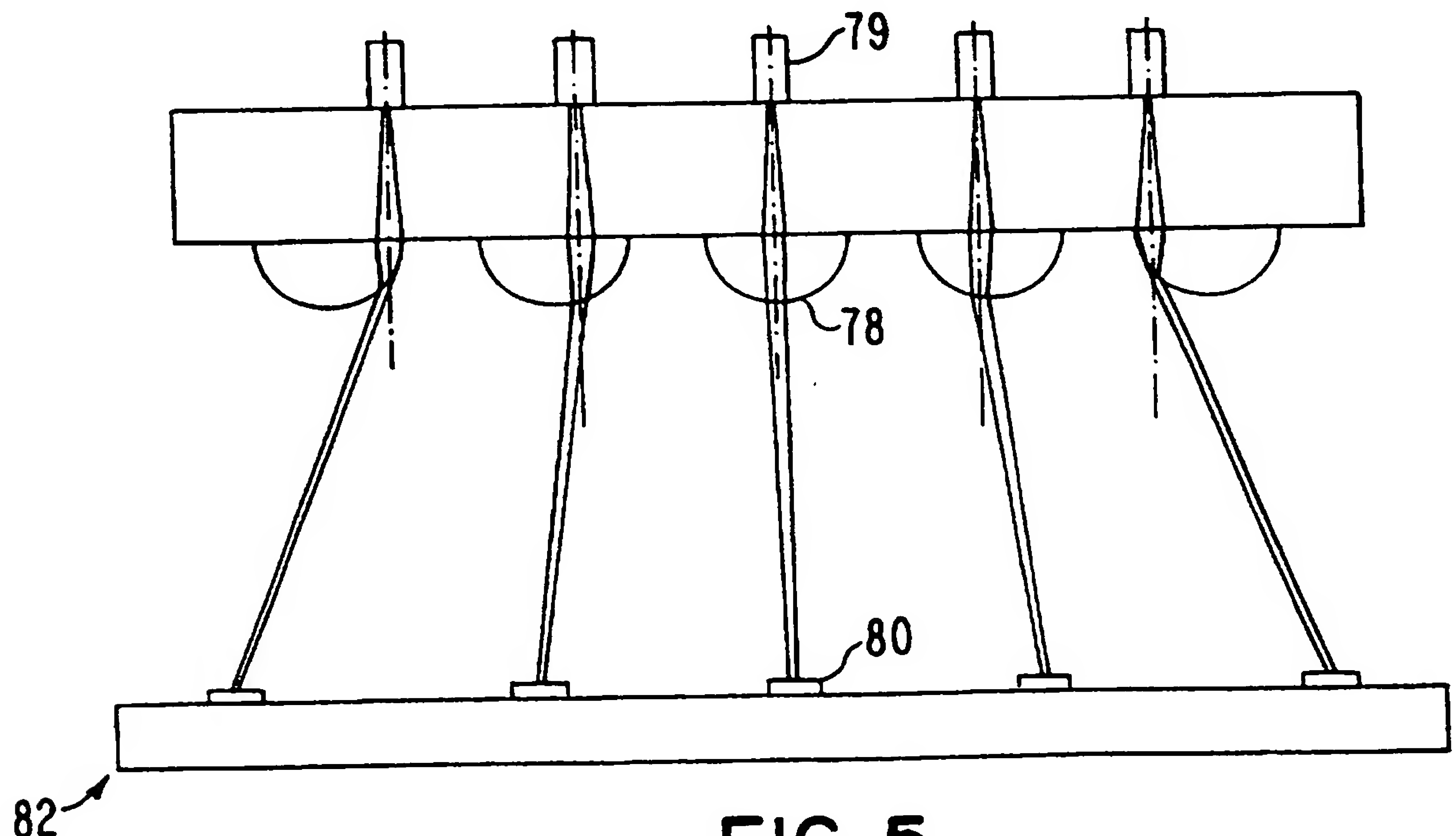


FIG. 5

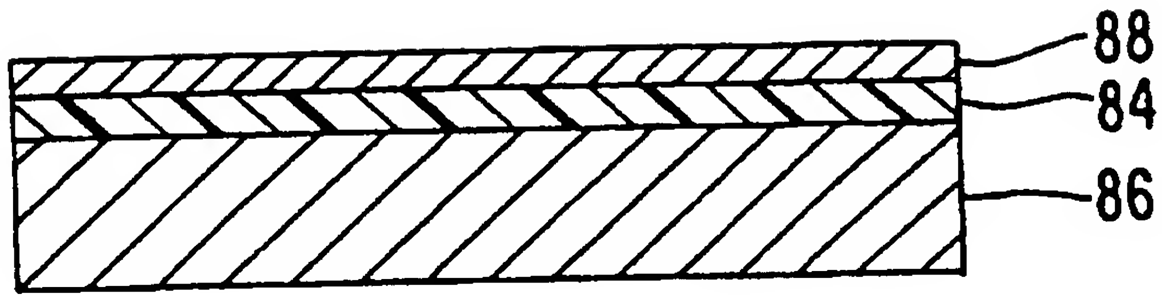


FIG. 6

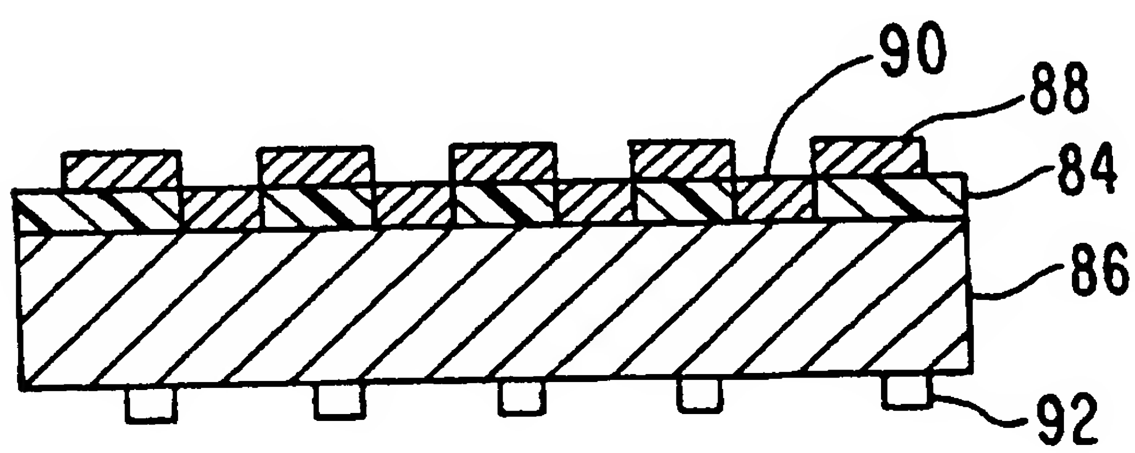


FIG. 7

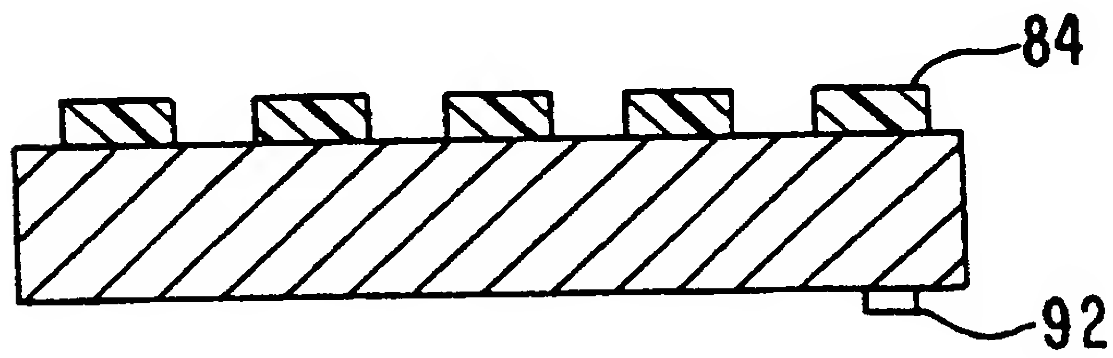


FIG. 8

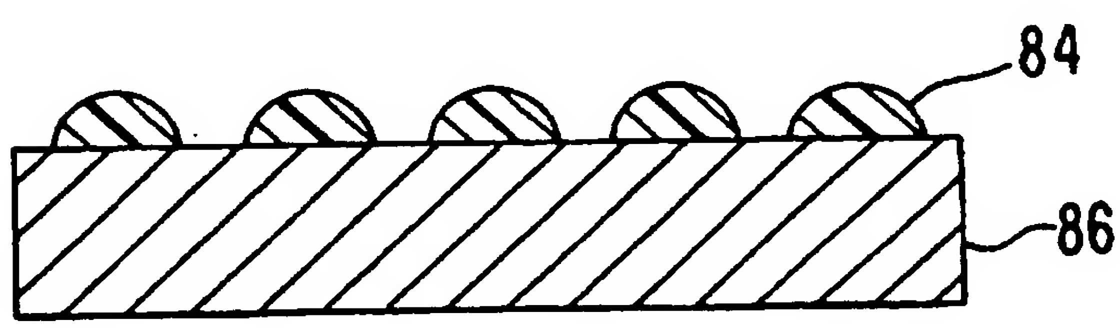


FIG. 12

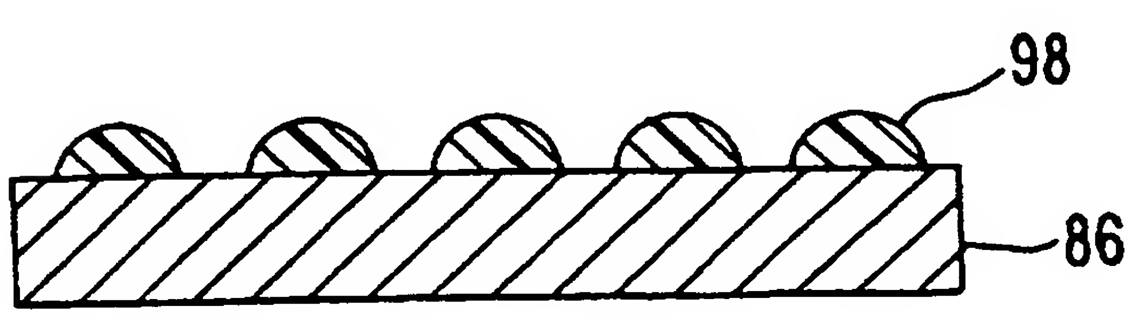


FIG. 13

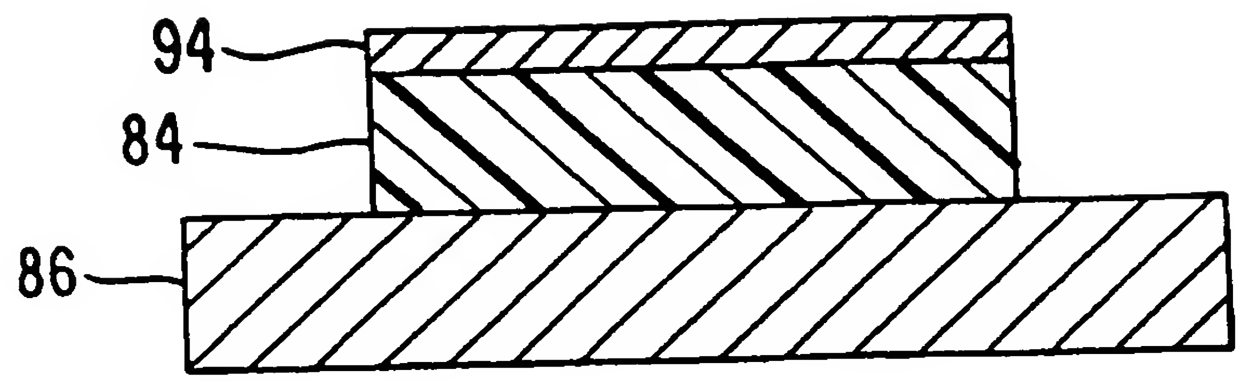


FIG. 9

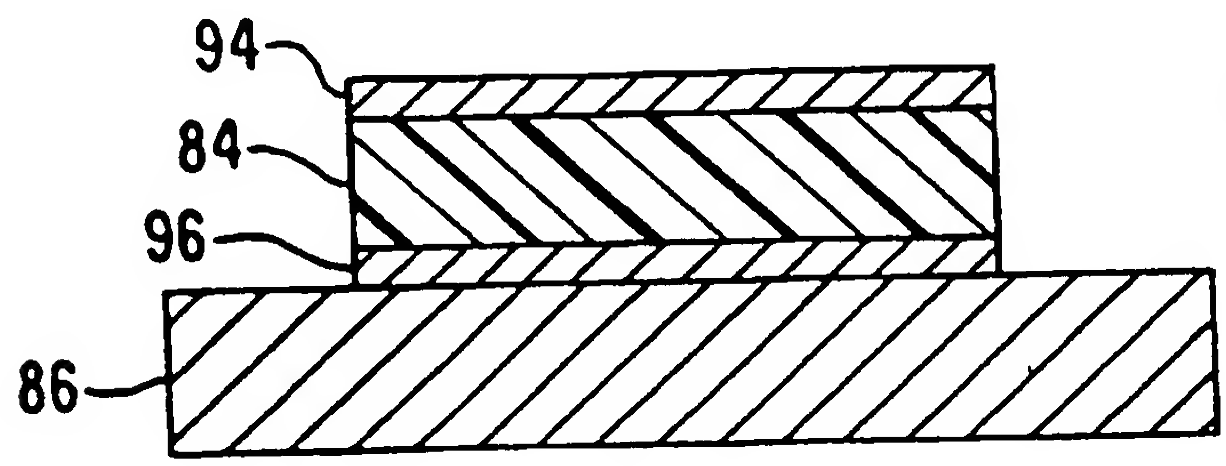


FIG. 10

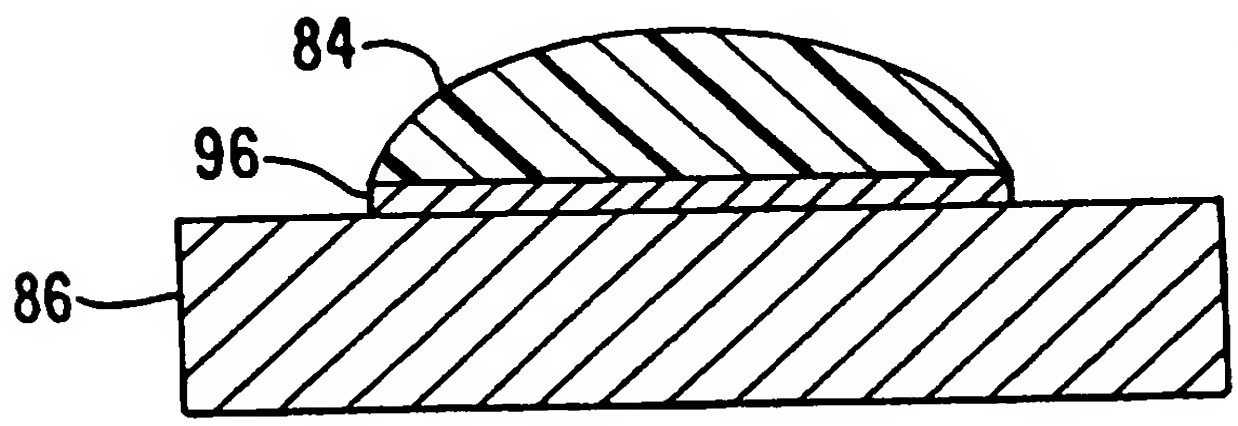
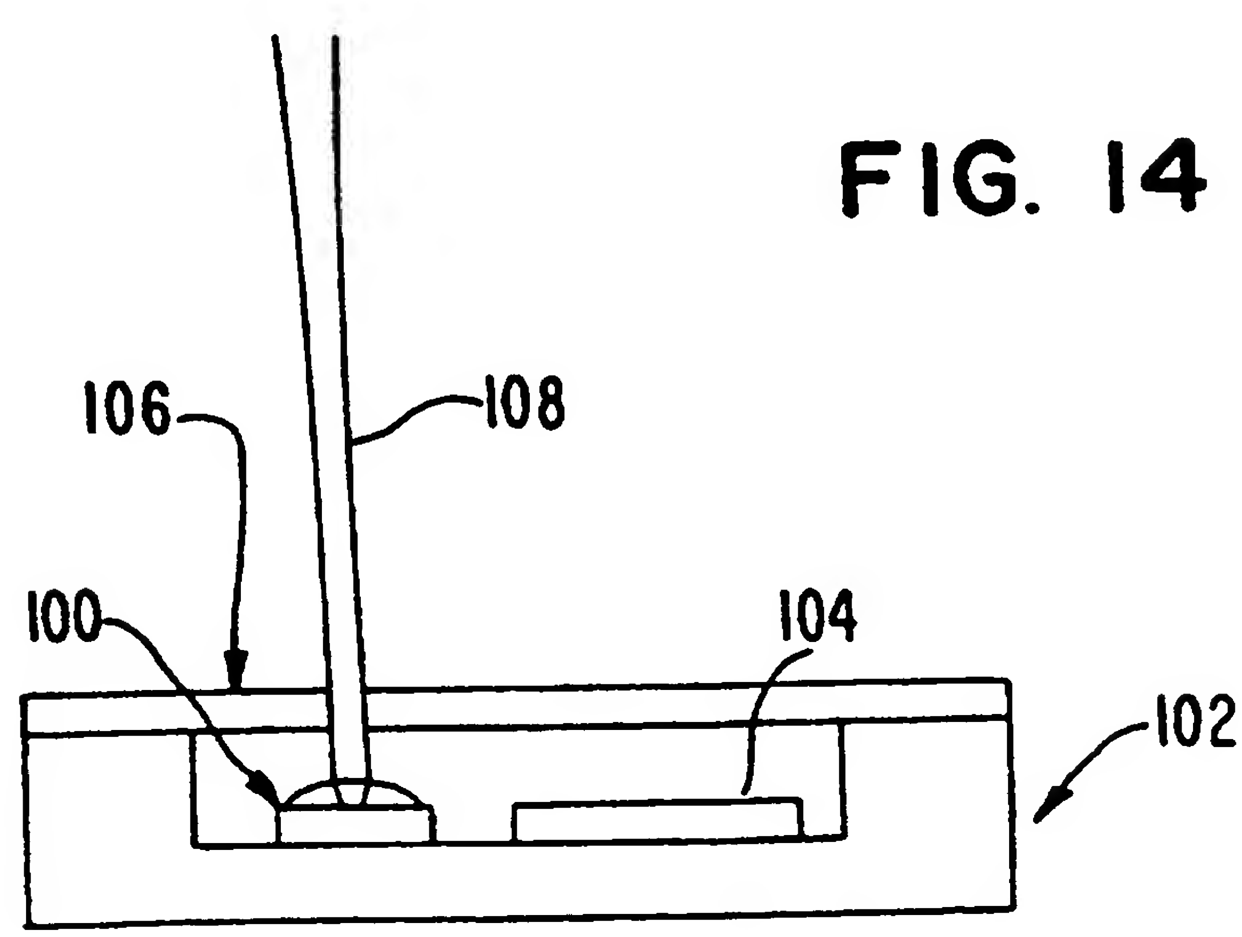


FIG. 11

FIG. 14



INTERNATIONAL SEARCH REPORT

Intei   al Application No
PCT/US 97/06126

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/085 H01S3/25 H01S3/025 H01L33/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ELECTRONICS LETTERS, vol. 31, no. 9, 27 April 1995, page 724/725 XP000517789 STRZELECKA E M ET AL: "MONOLITHIC INTEGRATION OF VERTICAL-CAVITY LASER DIODES WITH REFRACTIVE GAAS MICROLENSES"	1,2,4,5, 7-14,17, 18
Y	see the whole document ---	3,4,6,15
Y	CLEO'95, SUMMARIES OF PAPERS PRESENTED AT THE CONFERENCE ON LASERS AND ELECTRO-OPTICS, BALITIMORE, MA, USA, 22-26 MAY 1995 (IEEE CAT.NO. 95CH35800), pages 195-196, XP002035656 DU ET AL: "DIRECTIONAL BEAM CONTROL USING ON7OFF-AXIS HIGH EFFICIENCY DIFFRACTIVE OPTICS INTEGTRATED ON SUBSTRATE EMITTING VERTICAL CAVITY LASERS " see the whole document ---	1,3

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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3

Date of the actual completion of the international search	Date of mailing of the international search report
30 July 1997	28. 08. 97

Name and mailing address of the ISA	Authorized officer
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	EP 0 514 283 A (FUJITSU LTD) 19 November 1992 see column 6, line 17 - column 10, line 6; figures 4-6,8-10 ---	1,4,7,8 13
Y	IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 3, no. 9, 1 September 1991, pages 776-778, XP000225787 STEGMULLER B ET AL: "SURFACE EMITTING INGAASP/INP DISTRIBUTED FEEDBACK LASER DIODE AT 1.53 UM WITH MONOLITHIC INTEGRATED MICROLENS" see the whole document ---	1,4,13
Y	PATENT ABSTRACTS OF JAPAN vol. 018, no. 152 (E-1523), 14 March 1994 & JP 05 328233 A (HITACHI LTD;OTHERS: 01), 10 December 1993, see abstract ---	1,3
X Y	ELECTRONICS LETTERS, vol. 31, no. 1, 5 January 1995, page 44/45 XP000504157 BLUM O ET AL: "VERTICAL-CAVITY SURFACE-EMITTING LASERS WITH INTEGRATED REFRACTIVE MICROLENSES" see the whole document ---	1,2,9 1,6,15
X Y	OPTOELECTRONIC PACKAGING (CONF.), SAN JOSE, CA, USA, 1-2 FEB. 1996 (PROCEEDINGS OF THE SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING, , vol. SPIE 2691, pages 43-53, XP002035657 STRZELECKA ET AL. : "MONOLITHIC INTEGRATION OF REFRACTIVE LENSES WITH VERTICAL CAVITY LASERS AND DTECTORS FOR OPTICAL INTERCONNECTIONS " see page 47 - page 50; figures 6,8 ---	1,7-15, 17,18 1,6
A	PATENT ABSTRACTS OF JAPAN vol. 014, no. 156 (E-0908), 26 March 1990 & JP 02 014583 A (MITSUBISHI ELECTRIC CORP), 18 January 1990, see abstract ---	4,13
A	APPLIED OPTICS, vol. 27, no. 7, 1 April 1988, pages 1281-1284, XP000118684 POPOVIC Z D ET AL: "TECHNIQUE FOR MONOLITHIC FABRICATION OF MICROLENS ARRAYS" see the whole document ---	1-18

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3

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	J. ELECTROCHEM. SOC.: SOLID-STATE SCIENCE AND TECHNOLOGY, vol. 131, no. 10, October 1984, pages 2373-2380, XP002035658 WADA : "ION-BEAM ETCHING OF INP AND ITS APPLICATION TO THE FABRICATION OF HIGH RADIANCE INGAASP/INP LIGHT EMITTING DIODES" see the whole document -----	1-18

3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 97/06126

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 19 - 25
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
Claim 19 (part 2) and claims 20 - 23 missing from file.

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 97/06126

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0514283 A	19-11-92	JP 5055703 A	05-03-93
		DE 69201908 D	11-05-95
		DE 69201908 T	03-08-95
		US 5309468 A	03-05-94

CORRECTED VERSION*

PCT

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01S 3/085, 3/25, 3/025, H01L 33/00 — A1

(11) International Publication Number: WO 97/40558

(43) International Publication Date: 30 October 1997 (30.10.97)

(21) International Application Number: PCT/US97/06126

(22) International Filing Date: 14 April 1997 (14.04.97)

(30) Priority Data:
08/635,798 22 April 1996 (22.04.96) US

(71) Applicant: W.L. GORE & ASSOCIATES, INC. [US/US]; 551 Paper Mill Road, P.O. Box 9206, Newark, DE 19714 (US).

(72) Inventor: ROBINSON, Gerald, D.; Apartment 2-I, 3663 San Remo Drive, Santa Barbara, CA 93105 (US).

(74) Agents: CAMPBELL, John, S. et al.; W.L. Gore & Associates, Inc., 551 Paper Mill Road, P.O. Box 9206, Newark, DE 19714-9206 (US).

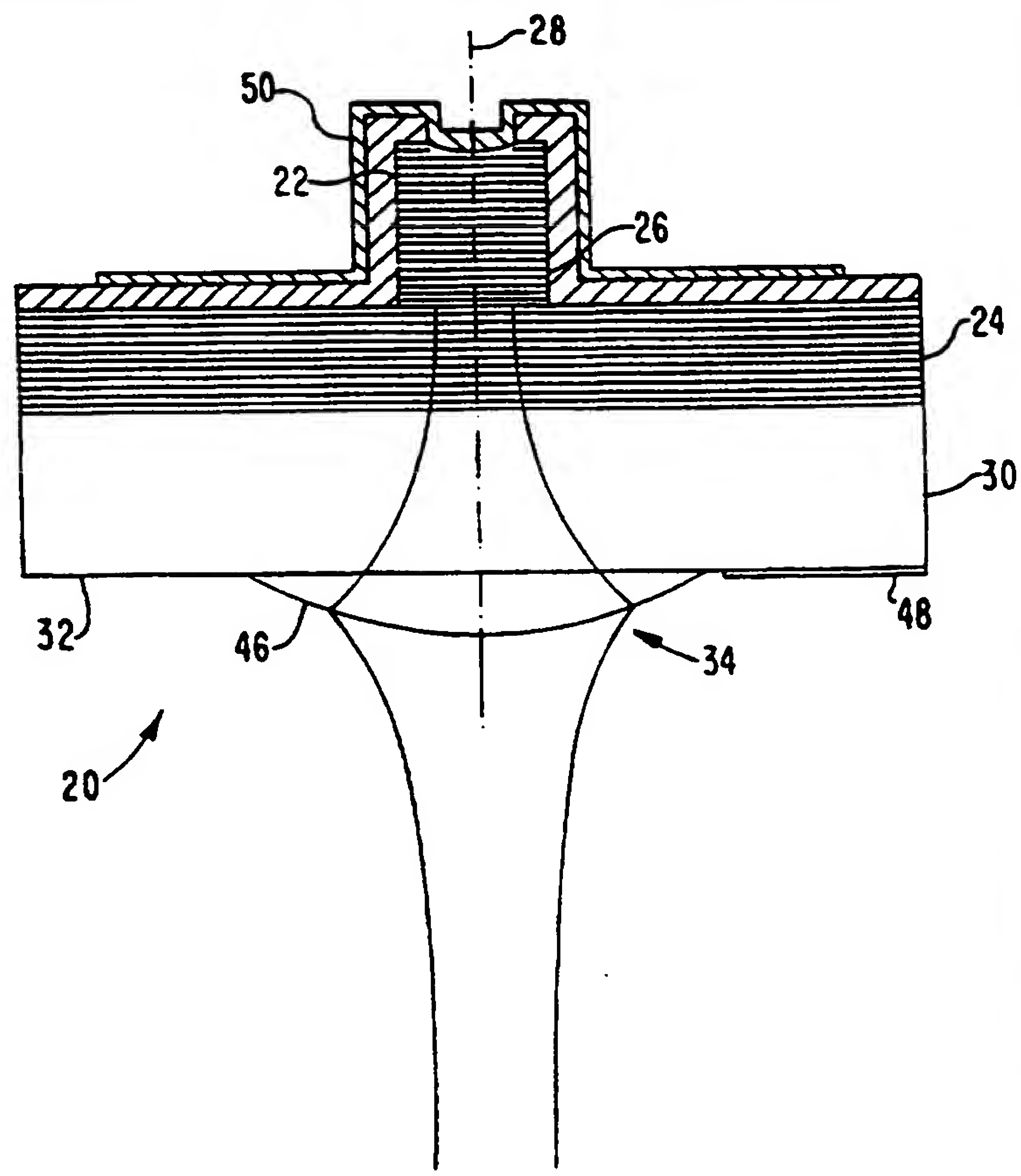
(81) Designated States: AL, AM, AT, AU, AZ, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: VERTICAL CAVITY LASERS WITH MONOLITHICALLY INTEGRATED REFRACTIVE MICROLENSES

(57) Abstract

Refractive microlenses (34, 38) are monolithically integrated into back-emitting vertical cavity lasers. A back-emitting VCL (20, 36) includes a front mirror, a back mirror being partially transmissive, an optical cavity interposed between the front mirror (22) and the back mirror (24), an active region within the optical cavity (26, 40) between the front and back mirrors, and a substrate (30). The substrate (30, 44) confronts the back mirror (24) and presents a light-emitting back surface (32). A refractive microlens (34, 38) is formed on the back surface (32) of the substrate (30, 44) with a photoresistive polymer or is monolithically integrated into the back surface (32) of the substrate (30, 44) using the photoresistive polymer. In microlens processing, poly(dimethylgluterimide) (PMGI), a deep ultraviolet photoresist is spin-coated on the polished back surface (32) of the substrate (30, 44) containing the fabricated VCL (20, 36). An imaging layer of conventional positive photoresist is spin-coated and patterned on the VCL. The PMGI is exposed to deep ultraviolet light using the patterned positive photoresist as a portable conformal mask. The exposed PMGI is then developed away and the positive photoresist is removed using acetone. The resultant structure is a cylinder of PMGI. A thin layer of the substrate around the PMGI cylinder is recessed. The PMGI cylinder is reflowed at 300 °C for 5-15 minutes. A parabolic lens shape of reflowed PMGI is obtained and is transferred to the substrate (30, 44) using reactive ion etching.



*(Referred to in PCT Gazette No. 07/1998, Section II)

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VERTICAL CAVITY LASERS WITH MONOLITHICALLY INTEGRATED REFRACTIVE MICROLENSES

FIELD OF THE INVENTION

This invention relates generally to vertical cavity lasers; and, more particularly to back-emitting vertical cavity lasers with monolithically integrated refractory microlenses.

BACKGROUND OF THE INVENTION

A vertical cavity laser (VCL) is a semiconductor laser consisting of a semiconductor layer of optically active material, such as gallium arsenide or indium gallium arsenide, sandwiched between highly-reflective layers of metallic material, dielectric material, epitaxially-grown semiconductor material or combinations thereof, the layers forming mirrors. Conventionally, one of the mirrors is partially reflective so as to pass a portion of the coherent light built up in the resonating cavity formed by the mirror/active layer sandwich. Laser structures require optical confinement and carrier confinement to achieve efficient conversion of pumping electrons to stimulated photons (a semiconductor may lase if it achieves population inversion in the energy bands of the active material). The standing wave in the cavity has a characteristic cross-section giving rise to an electromagnetic mode. A desirable electromagnetic mode is the single fundamental mode, for example, the HE_{11} mode of a cylindrical waveguide. A single mode signal

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from a VCL is easily coupled into an optical fiber, has low divergence and is inherently single frequency in operation.

An important commercial application of vertical-cavity lasers is in both guided wave and free space computer interconnections. Previous practice requires expensive and time consuming active alignment techniques requiring micro-machined features and precision micro-manipulators for mounting discrete focusing and beam collimating discrete components. A need continues for better beam focusing and beam collimating techniques, particularly for guided wave and free space computer interconnections.

SUMMARY OF THE INVENTION

Better laser beam focussing and laser beam collimating capability for vertical cavity lasers and optical detectors can be achieved by monolithically integrating refractory microlenses into back-emitting vertical cavity lasers (VCLs) and optical detectors in accordance with the principles of the invention. Such a back-emitting VCL includes a front mirror, a back mirror, an optical cavity interposed between the front and back mirrors, an active region within the optical cavity, and a substrate. The substrate confronts the back mirror and presents a light-emitting back surface. A refractory microlens is formed on the back surface of the substrate with a photoresistive polymer, or is monolithically integrated into the back surface of the substrate

BNSDOCID: <WO 9740558A1_IA>

using the photoresistive polymer in a reactive ion etching process. Monolithic integration of refractory microlenses into VCLs eliminates the cumbersome alignment processes of previous practice because fabrication of the lens is part of the VCL processing procedure. Microlenses fabricated into the back lens surface of back-emitting VCLs have a high refractory index (matching that of the substrate from which they are made). This enables high numerical aperture (NA) lenses to be produced.

Arrays of VCLs with associated arrays of integral microlenses can be fabricated. By controlling the spacing of the microlenses with respect to the spacing of the VCLs in the respective arrays, emitted laser beams can be made to diverge in travel toward an optical detector, or can be made to converge to one point of the optical detector.

In an illustrative embodiment, integrated microlens fabrication includes reflowing (i.e., controlled melting), of photoresist into a microlens having a parabolic cross-section. This microlens is transferred, using reactive ion etching (RIE), to the backside of a III-V compound (e.g., gallium arsenide (GaAs) or indium phosphide (InP)) semiconductor substrate of a back-emitting VCL.

Poly(dimethylgluterimide) ("PMGI"), a deep ultraviolet (UV) photoresist, is used as a sacrificial mask. PMGI is spin coated on the polished backside of the substrate(s) containing the fabricated VCL(s); it should be noted that many VCLs or

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optical detectors can be manufactured in a wafer substrate. An imaging layer of conventional positive photoresist is spin coated on the VCL substrate. The conventional positive photoresist is patterned using an infrared (IR) mask aligner to precisely align (to a tolerance of <1 micron) the lens center to the central vertical axis of the VCL. The PMGI beneath the patterned positive photoresist is exposed to deep UV using the patterned positive photoresist as a portable conformal mask (PCM) that is opaque to deep UV radiation.

The exposed PMGI is then developed away and the positive photoresist is removed using acetone. The resultant structure is a cylinder of PMGI. The thickness and diameter of the cylinder of PMGI can be controlled to less than 1 micron.

A thin layer of the substrate (< 0.5 micron) around the PMGI cylinder is recessed with a solution of $H_3PO_4:H_2O_2:H_2O$ (1:5:50). This results in lithographically defined PMGI cylinders on GaAs pedestals. The GaAs pedestals constrain by surface tension the PMGI during reflow (melting) to a fixed diameter.

The PMGI cylinders are reflowed at a temperature of 300°C for 5-15 minutes, depending on the thickness of the PMGI. Near-parabolic cross-sectional shapes of reflowed PMGI are obtained.

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This near-parabolic cross-sectional shape is transferred to the VCL substrate using reactive ion etching (RIE). The RIE stage uses Cl_2 typically at 1 mT and 350 Vdc (power 60W) bias in a parallel plate chamber. Transferring the shape integrates a microlens into the VCL substrate.

The radius of curvature in a cross-section of the created microlens can be modified in the RIE stage by adjusting the etch conditions to change the relative etch rates of PMGI and the semiconductor substrate. By varying (a) the initial PMGI thickness, (b) diameter, and (c) relative etch rate, microlenses having a numerical aperture (NA) of up to 0.4 and focal lengths from 10 to 1000 microns can be achieved. After lens fabrication, the back surface can be covered with a silicon oxide (SiO) anti-reflection coating to minimize optical feedback.

A similar technique for monolithically integrating microlenses into indium phosphide (InP)-based substrates employs different etchant chemicals and etching rates. The similar technique is also applicable to GaAs-based substrates.

Other features and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawing, which illustrate, by way of example, the features of the invention.

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BRIEF DESCRIPTION OF THE DRAWING

In the drawing:

FIG. 1 shows a refractory microlens formed on a back-emitting VCL;

FIG. 2 shows a back-emitting VCL having two substrate layers and a monolithically integrated refractory microlens;

FIG. 3 shows a back-emitting VCL array with integrated microlenses focussing into a fiber array;

FIG. 4 shows a back-emitting VCL array with a convergent microlens arrangement;

FIG. 5 shows a back-emitting VCL array with a divergent microlens arrangement;

FIGS. 6-13 schematically present a process for fabricating integrated microlenses; and

FIG. 14 shows a hermetically-sealed package for VCLs with integrated microlenses for free-space applications.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

According to the principles of the invention, back-emitting vertical cavity lasers (VCLs) or optical detectors are integrated with refractive microlenses. A back-emitting VCL 20 includes a front mirror 22, a back mirror 24, an optical cavity 26, which includes an active region, interposed between the front mirror 22 and the back mirror 24 having a central vertical axis 28, and a substrate 30 confronting the back mirror and presenting

BNSDOCID: <WO 9740558A1 IA>

a light-emitting back surface 32. A refractory microlens 34 is disposed on the back surface 32.

The front mirror 22 and the back mirror 24 each include a stack of alternating layers of AlGaAs and GaAs. The optical cavity 26 includes InGaAs as the active medium. The substrate 30 includes one or more semiconductor layers selected from the group consisting of GaAs, InP, and combinations thereof.

FIG. 2 shows a back-emitting VCL 36 having two semi-conductor layers monolithically integrated with a refractory microlens 38. The VCL 36 includes an optical cavity 40 consisting of an InGaAs active medium in confronting relationship with an InP substrate layer 42. The InP substrate layer 42 is wafer-fused to a GaAs substrate layer 44. The refractory microlens 38 is monolithically integrated directly into the GaAs substrate layer 44.

The refractory microlens 34 (FIG. 1) can consist of a photosensitive polymer such as poly(dimethylgluterimide), denoted "PMGI" in the art, or the refractory microlens 34 can be monolithically integrated into the substrate 30 of the back-emitting VCL 20. An optional anti-reflection coating 46 can be formed on the refractory microlens 34.

An n-type electrode 48 and a p-type electrode 50 are applied to the VCL 20 so that the VCL 20 can be electrically pumped. The p-type electrode 50 is fabricated from AuZnAu and

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applied to the front mirror 22. The n-type electrode 48 is fabricated from CrAu and applied to the substrate 30.

Refractive microlenses are etched on the back side of VCL semiconductor substrates in a wafer-scale fabrication process according to the principles of the invention. This fabrication process enables arrays of refractory microlenses to be combined and juxtaposed with arrays of back-emitting VCLs created in a substrate wafer.

FIG. 3 shows an array 52 of back-emitting VCLs formed on a substrate wafer 54. An array 56 of refractory microlenses is formed on the substrate wafer. The array of microlenses can be formed of a photoresistive polymer such as PMGI, or can be monolithically integrated directly into the substrate wafer for free-space interconnections. When such a VCL array is driven to emit laser light, the array of microlenses can be used to collimate and focus the emitted laser light 58 toward a target, such as an optical detector or an optical detector array 60. The center 62 of the refractory microlens surface can be aligned with the central vertical axis 64 of the optical cavity, as shown in FIG. 3, to focus or collimate the individual laser beams. The center 62 can also be displaced from the central vertical axis to focus multiple laser beams in a single spot, as shown in FIG. 4, or to spread out the laser beams as shown in FIG. 5.

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The spacing between microlenses in an array of microlenses can be varied with respect to the spacing of VCLs in an array of VCLs using a photolithographic mask to support a convergent laser light emission pattern (FIG. 4) or a divergent laser light emission pattern (FIG. 5).

In the convergent laser light emission pattern shown in FIG. 4, the light from all the VCLs converge on the same point. The center of each microlens is displaced from the central vertical axis of its associated VCL by an offset. For the middle VCL 66 of the VCL array 68 the offset between the center of its associated microlens 70 and the central vertical axis 72 of the VCL 66 is zero. The middle VCL 66 and its associated microlens 70 are aligned with a receiving point 74 of an optical detector 76. Other microlenses on either side of the middle microlens 70 are offset from their associated VCLs so that the emitted laser light converges on the receiving point 74. For a microlens associated with a VCL, the offset in the direction toward the middle microlens 70 increases with the distance of the VCL from the middle VCL 66. This offset spacing of the microlenses with respect to the spacing of the VCLs causes emitted laser light focussed by each microlens to converge to the receiving point 74 in travel toward the optical detector array 76. By selectively positioning the optical detector array linearly from the microlens array 77, converging laser beams from the VCL array can be combined at the receiving point. This can be useful for

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increasing power output required for a particular application. For example, the output laser emissions from ten 5 mW VCLs in an array can be converged to provide 50 mW of power to the receiving point.

In the divergent laser light emission pattern shown in FIG. 5, the spacing between microlenses causes emitted laser light focussed by each microlens to diverge in travel toward an optical detector array. The center of each microlens is displaced from the central vertical axis of its associated VCL by an offset. The offset of the middle microlens 78 with respect to the associated middle VCL 79 is zero. The middle VCL 79 and its associated middle microlens 78 are aligned with a middle optical detector 80 of the optical detector array 82.

Microlenses on either side of the middle microlens 78 are offset from their associated VCLs so that the emitted laser beams diverge in travel toward the detector array 82. For a microlens associated with a VCL, the offset between the microlens and the associated VCL in the direction away from the middle microlens 78 increases with the distance of the VCL from the middle VCL 79. This accommodates various spacing between optical detectors in the detector array 82.

Monolithically integrating microlenses into the back surface of back-emitting VCLs enhances laser beam focusing and collimation for the VCLs. This achievement greatly simplifies free space and/or fiber alignment packaging and testing of VCLs.

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A first microlens processing embodiment of the invention is described for gallium arsenide (GaAs)-based VCLs and/or optical detectors. A second microlens processing embodiment of the invention for indium phosphide (InP)-based VCLs or optical detectors is similar to the first embodiment. However, etching gases and resist thicknesses are different to accommodate the difference in etching rates, as described subsequently. Both processing embodiments are practiced subsequent to fabrication of the VCLs or optical detectors.

In the first processing embodiment, microlenses are monolithically integrated into the polished back side of a gallium arsenide (GaAs) substrate containing pre-processed VCL or optical detector arrays. This integration process is depicted schematically for a series of process steps in FIGS. 6-13.

Referring to FIG. 6, poly(dimethylgluterimide), (PMGI), a positive radiation sensitive resist 84, commercially available as: *SF 15, Microlithography Chemical Corp., Newton, MA,* is applied onto the polished back side of the GaAs wafer 86. The wafer 86 is spun, using a conventional photoresist spin coater, at 3500 ±5 RPM for 30 seconds. The PMGI coating 84 is baked on a hot plate for 5 min. ±30 sec., at 200 ±5°C. The resultant thickness of the PMGI 84 will be 3 microns ±1000 angstroms thick.

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These steps are repeated until the desired thickness is achieved. Typically a total thickness of 6 microns is pre-selected and used to achieve a lens with the desired radius of curvature for a 200 micron diameter lens in GaAs.

The target thickness of PMGI is easily achieved by applying two coats of PMGI with controlled spin speeds. For example, the first layer is spun at 3500 RPM for a 3 micron thickness, which is followed by a second layer of PMGI spun at 4500 RPM for a total thickness of 5 microns.

Various viscosities of PMGI may also be used for finely tuned control of thickness.

Precision tailoring of the thickness can also be achieved by etching the PMGI 84 in an oxygen plasma using a conventional parallel plate plasma reactor. This procedure is rarely required since the controlled spin speeds recited herein produce PMGI thicknesses well within the tolerances required to achieve the desired lens shape.

The selected thickness of the PMGI 84 is based on the diameter and radius of curvature desired for the resultant GaAs lens. When the relative etch rates of the PMGI and the GaAs have been determined for controllable etching parameters for a given reactive ion etcher, consistent results are easily obtained.

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A conventional positive resist 88, e.g., *AZ1420, Hoechst Celanese Corp., Somerville, NJ,* or an equivalent, is applied onto the PMGI coating 84. The positive resist coating 88 is spun at 4000 ±100 RPM for 30 ±5 sec. The positive resist coating 88 is baked on a hot plate for 30 ±5 sec. at 90 ±5°C.

A photolithographic contact mask aligner with infrared (IR) viewing capability, e.g., *Karl Suss MJB3-IR, Waterbury Center, VT,* presents a light field photolithographic mask containing desired patterns. The light field photolithographic mask is aligned to the laser or optical detector. The IR mask aligner permits observation of the VCLs or optical detectors through the substrate permitting precise alignment to tolerances of 1 micron or better.

Referring to FIG. 7, the positive resist coating 88 is exposed to UV light, typically 7.5 mW/cm^2 at a wavelength of 405 nm for 15 sec. The exposed positive resist 88 is developed using an appropriate developer, e.g., Hoechst AZ 4000, or equivalent. The developed positive resist 88 has a pattern that corresponds to the light field photolithographic mask and acts as a portable conformal mask (PCM) for defining the PMGI.

The resist coated substrate 86 is flood-exposed with deep ultraviolet light using a deep ultraviolet light source, e.g., *OAI (Optical Associates, Inc.), Milipitas, CA* or *Fusion Semiconductor Systems, Rockville, MD,* or an equivalent. Flood exposure is typically at 10 mW/cm^2 for 5 min. at 457 nm wave-

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length. The exposed PMGI 84 is developed in *Shipley SAL 101, Shipley Co., Newton, MA,* or an equivalent, developer for 2 min. ±10 sec.

The positive resist pattern is opaque to deep ultraviolet light and permits deep ultraviolet radiation of the PMGI 84 only in the areas 90 clear of the positive resist. Exposure and development times depend upon the power of the deep ultraviolet light of the source used.

Flood exposure of the resist coated substrate 86 can be repeated, if required, until the PMGI 84 is removed in the areas 90 not covered by the positive resist 88.

The positive resist 88 is then removed by applying acetone. The acetone does not attack the PMGI 84. Such acetone application results in a cylinder of PMGI 84, as shown in FIG. 8. The diameter and thickness of the cylinder of PMGI 84 is precisely defined and aligned to the VCL 92 or detector.

Referring to FIG. 9, a layer 94 of positive photoresist is then applied to the device side of the substrate 86. The positive photoresist layer 94 is cured on a hot plate at 90°C for 1-2 min. This step is done to protect the devices during the following step.

A solution for etching GaAs, consisting of phosphoric acid/hydrogen peroxide/water, $H_3PO_4:H_2O_2:H_2O$ (1:5:50), is prepared. The exposed GaAs substrate 86 circumscribing the PMGI cylinder 84 is etched in the prepared etch solution for 15 ±2 sec. to remove

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a thin layer of the GaAs (~0.5 micron). The area is rinsed with deionized water (DI H_2O) and blow-dried with dry nitrogen. This leaves the PMGI cylinders 84 on GaAs pedestals 96 (shown in FIG. 10) which constrain, by surface tension, the PMGI 84 during reflow to a fixed diameter. The positive resist 94 is removed by applying acetone. Such application is followed with an isopropyl alcohol (IPA) rinse and blown dry.

The substrate 86 and PMGI cylinder 84 on the pedestal 96 are placed in an oven filled with nitrogen. The temperature of the oven is made to be above the glass transition temperature of the PMGI, which is about ~197°C. The oven temperature is typically in the range of 290-300°C, and heating to reflow the PMGI is for 5 to 30 minutes, depending upon the PMGI thickness.

Optionally, the shape of the reflowed PMGI can be confirmed using a surface profilometer. If the profile is not optimum, an additional reflow may be performed or the profile can be modified using an oxygen plasma as described previously. This is rarely required because of the precision obtained using these process steps. Referring to FIGS. 11 and 12, a PMGI microlens 84 formed at this stage of the process can be used as a collimating or focusing lens.

Numerous parallel plate reactive ion etching (RIE) systems are commercially available for reactive ion etching. A parallel plate RIE system is used to transfer the lens formed in the reflowed PMGI 84 into the GaAs substrate 86 to create a

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monolithically integrated microlens 98 in the substrate 86, as shown in FIG. 13.

Various etching gases (e.g., borontrichloride (BCl_3), silicontetrachloride ($SiCl_4$) and chlorine (Cl_2)) can be optimized in various combinations to produce superior quality microlenses, depending upon the plasma etcher configuration and etching parameters (e.g., gas flow, chamber pressure, bias voltage, etc.) of a particular RIE system.

In the first embodiment, the RIE system incorporates a vertical parallel plate configuration and uses Cl_2 etchant gas.

The substrate is placed, device side down, using a low vapor pressure, thermally conductive adhesive, e.g., Mung, to attach the substrate to the cathode plate of the vertical parallel plate configuration. A test sample with PMGI, of thickness equaling that of the reflowed PMGI, is also placed on the cathode plate to be used as an etch monitor.

The RIE system incorporates a load-lock for evacuation of the cathode with the mounted substrate and the etch monitor to permit insertion into the main chamber which is under high vacuum. This is not a necessary requirement, but is useful since the main chamber does not have to be vented to atmosphere to load the substrate. Most commercially available RIE systems provide a load-lock as an option.

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Typical etching parameters of the RIE system used are: Cl_2 at 7.5 sccm (standard cubic centimeters/min.), pressure at 1 mT (milliTorr), 350 V d.c. bias at 60 watts. A typical etch rate of the PMGI is 1200 angstroms/min. The etching of the PMGI is monitored by directing the light emitted from a helium\neon (HeNe) laser through an optical port in the RIE chamber onto the PMGI test sample for etch monitoring. The reflected light from the PMGI test sample is directed into a silicon photodetector. The output of the silicon photodetector is used to drive an X-Y recorder. The output of the detector results in a sinusoidal display on the chart recorder due to the interference as a function of the thickness of the PMGI. The periods of the sinusoidal patterns are 1/4 wavelength of the HeNe laser (1530 angstroms). By knowing the precise etch rate of the PMGI, which is related to the predetermined etch rate of the GaAs, the etching process can be terminated at the proper time to prevent excessive etching of the GaAs.

Following the etching process the substrate is removed from the RIE chamber. The substrate is rinsed with deionized water to remove any residual Cl_2. Removing the mounting adhesive with acetone or IPA completes microlens 98 (FIG. 13) fabrication.

Following fabrication of a microlens, an optional SiO anti-reflection coating can be deposited on the lens side of the substrate to prevent light reflection into the VCL or optical detector.

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Back-emitting GaAs/AlGaAs VCLs with extremely minimal far-field beam divergence can be fabricated according to the procedure taught herein. VCLs having a single mode in the transverse direction were fabricated and operated up to their peak power levels. Their beam profile was measured by scanning a detector with a 50 micron diameter pinhole across the beam. Without a lens, the divergence angle of beams from a 7 micron diameter device was 6.5°. With a lens the divergence was decreased to achieve a near-collimation condition. The divergence angles were 2.2 and 1.9° with lenses of radii of curvature of 560 and 316 microns, respectively.

In a second microlens processing embodiment of the invention, refractory microlenses can be made integral with indium phosphide (InP)-based substrates in VCLs and optical detectors. The procedure for fabricating microlenses in indium phosphide (InP) is the same as the gallium arsenide (GaAs) procedure taught herein with the exception of the etching system and gases used.

To fabricate the microlenses into an InP substrate, a Plasma-Therm parallel plate reactive ion etcher (RIE) is used. The etching gasses are: brominetrichloride:silicontetra-chloride:chlorine, $BrCl_3:SiCl_4:Cl_2$, 25 standard cubic centimeters/minute (sccm):5sccm:2sccm at a pressure of 10 milliTorr (mT). By adjusting the RF power and the pressure, the relative etch rates of the InP and the PMGI can be controlled.

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This is important for controlling the shape of the resultant lens and eases photolithographic requirements.

The second processing embodiment for integrating microlenses into InP-based substrates works for GaAs-based substrates with only slight changes in the etching parameters. This procedure significantly enhances the microlens integrating process and ensures that manufacturing viability can be realized.

It is contemplated that a VCL 100 (or VCL array) with integrated microlens(es) can be hermetically sealed in a commercial package 102, as shown in FIG. 14. The commercial package 102 can include driver and receiver circuitry 104 for free-space communications. The commercial package 102 shown in FIG. 14 presents an anti-reflection coated window 106 (e.g., made of sapphire) which passes an outgoing collimated laser beam 108 while preventing optical feedback into the package 102.

While several particular forms of the invention have been illustrated and described, it will also be apparent that various modifications can be made without departing from the spirit and scope of the invention.

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WHAT IS CLAIMED IS:

1. An optically focussed back-emitting vertical cavity laser (VCL), comprising:

a front mirror;

a back mirror being partially transmissive;

an optical cavity interposed between said front mirror and said back mirror and having a central vertical axis;

an active region within said optical cavity between said front mirror and said back mirror;

a substrate confronting said back mirror and presenting a back surface; and

a refractory microlens disposed on said back surface.

2. The back-emitting VCL of claim 1, wherein:

the center of the microlens is aligned with said central vertical axis.

3. The back-emitting VCL of claim 1, wherein:

the center of the microlens is displaced from said central vertical axis.

4. The back-emitting VCL of claim 1, wherein:

said substrate comprises a compound semiconductor selected from the group consisting of gallium arsenide and indium phosphide.

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5. The back-emitting VCL of claim 1, further comprising:

an anti-reflection coating formed on said refractory microlens.

6. The back-emitting VCL of claim 1, wherein:

said refractory microlens includes PMGI.

7. The back-emitting VCL of claim 1, wherein:

said refractory microlens is integral with said back surface.

8. The back-emitting VCL of claim 1, further comprising:

a p-type electrode applied to said front mirror; and

an n-type electrode applied to said substrate.

9. The back-emitting VCL of claim 1, wherein:

said substrate is an n-type substrate.

10. A method of integrating a refractory microlens into a back-emitting vertical cavity laser (VCL) having a central vertical axis and including a substrate which presents a back surface, comprising the following steps:

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(A) coating PMGI on the back surface of the substrate;

(B) forming a portable conformal mask on the PMGI which is positioned with respect to the central vertical axis of the VCL;

(C) removing the PMGI exposed by the portable conformal mask;

(D) removing the portable conformal mask to form a PMGI cylinder;

(E) recessing a section of the substrate circumscribing the PMGI cylinder; and

(F) reflowing the PMGI cylinder into a microlens.

11. The method of claim 10, further comprising the step:

transferring the microlens using reactive ion etching into the back surface of the substrate.

12. The method of claim 11, further comprising the step:

etching the PMGI cylinder and the substrate with chlorine.

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13. The method of claim 10, wherein:

the substrate comprises a compound semiconductor selected from the group consisting of gallium arsenide and indium phosphide.

14. The method of claim 10, wherein step (B) includes the steps:

spin coating an imaging layer of conventional positive photoresist on the PMGI; and

patterning the imaging layer to form the portable conformal mask.

15. The method of claim 10, wherein step (C) includes the steps:

exposing the PMGI to deep ultraviolet radiation; and

developing the exposed PMGI.

16. The method of claim 10, further comprising the step:

polishing the back surface of the substrate before coating the PMGI.

17. The method of claim 10, wherein:

in step (F), the PMGI is reflowed at approximately 300 °C for a duration in the range of 5 to 15 minutes.

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18. The method of claim 10, wherein:

the microlens has a parabolic cross-sectional configuration.

19. A method of integrating a refractory microlens into a back-emitting vertical cavity laser (VCL) having a central vertical axis and including a substrate which presents a back surface, comprising the following steps:

(A) applying a PMGI coating onto the back surface of the substrate;

(B) applying a patterned positive resist coating defining a light field photolithographic mask to the PMGI coating;

(C) aligning the patterned positive resist coating and the central vertical axis;

(D) developing the patterned positive resist coating;

(E) flood exposing the patterned positive resist coating with deep ultraviolet light to remove the PMGI in the areas exposed by the patterned positive resist coating;

(F) removing the patterned positive resist coating to form a PMGI cylinder;

(G) etching a section of the substrate circumscribing the PMGI cylinder to dispose the PMGI cylinder on a substrate pedestal;

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(H) heating the substrate and the PMGI cylinder in a nitrogen atmosphere to reflow the PMGI cylinder into a microlens; and

(I) reactive ion etching the microlens with an etchant gas to transfer the microlens into the substrate.

20. The method of claim 19, further comprising the step:

repeating step (A) to achieve a preselected coating thickness of PMGI.

21. The method of claim 19, wherein step (D) includes the step:

exposing the positive resist coating to ultraviolet light.

22. The method of claim 19, further comprising the step:

repeating step (E) until the PMGI is removed in the areas exposed by the positive resist coating.

23. The method of claim 19, wherein:

the etchant gas in step (I) is chlorine.

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24. The method of claim 19, wherein:

the substrate comprises a compound semiconductor selected from the group consisting of gallium arsenide and indium phosphide.

25. The method of claim 19, further comprising the step:

disposing the back-emitting VCL in a hermetically-sealed package, which includes circuitry for free-space communication applications.

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FIG. 1

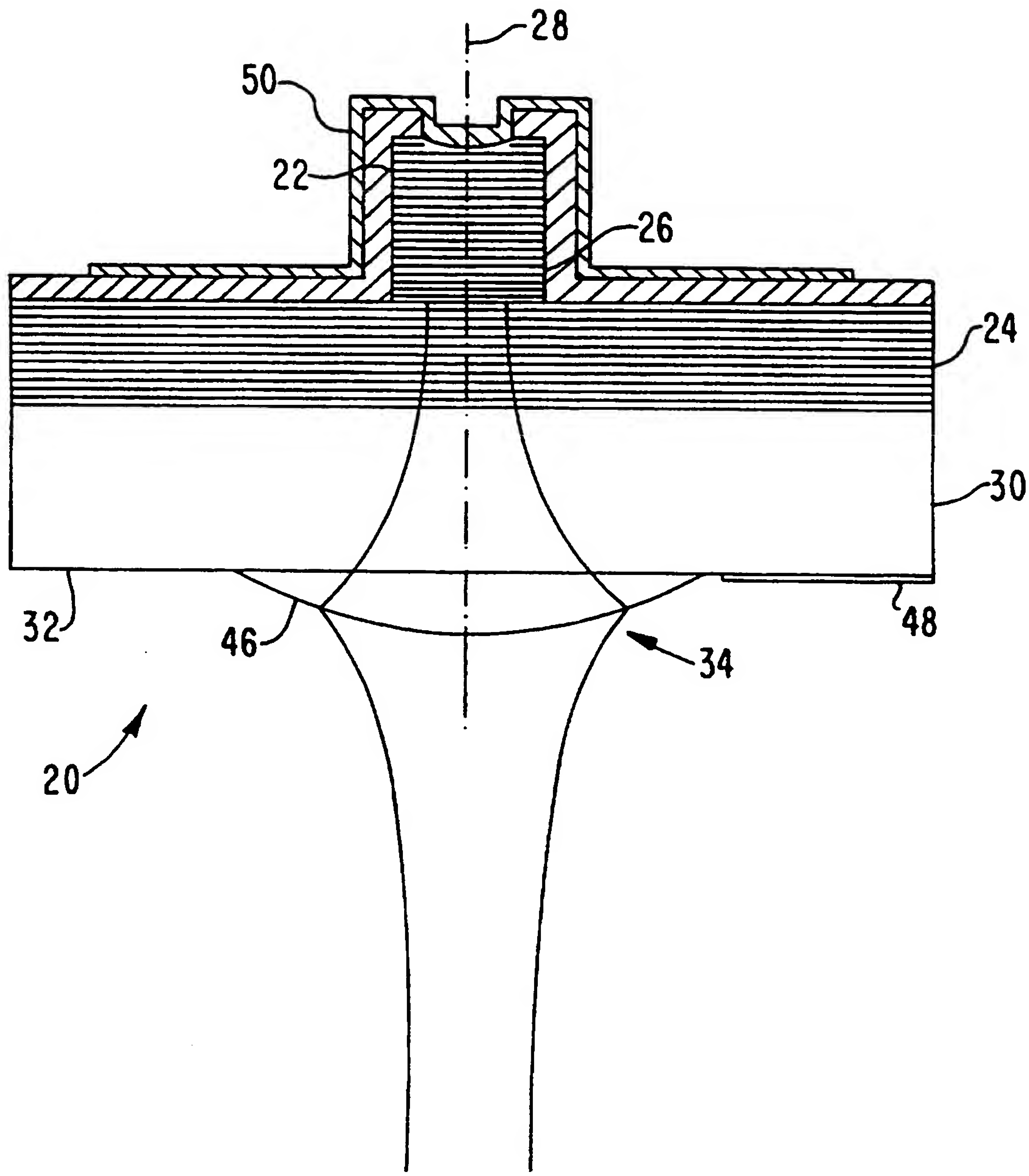


FIG. 2

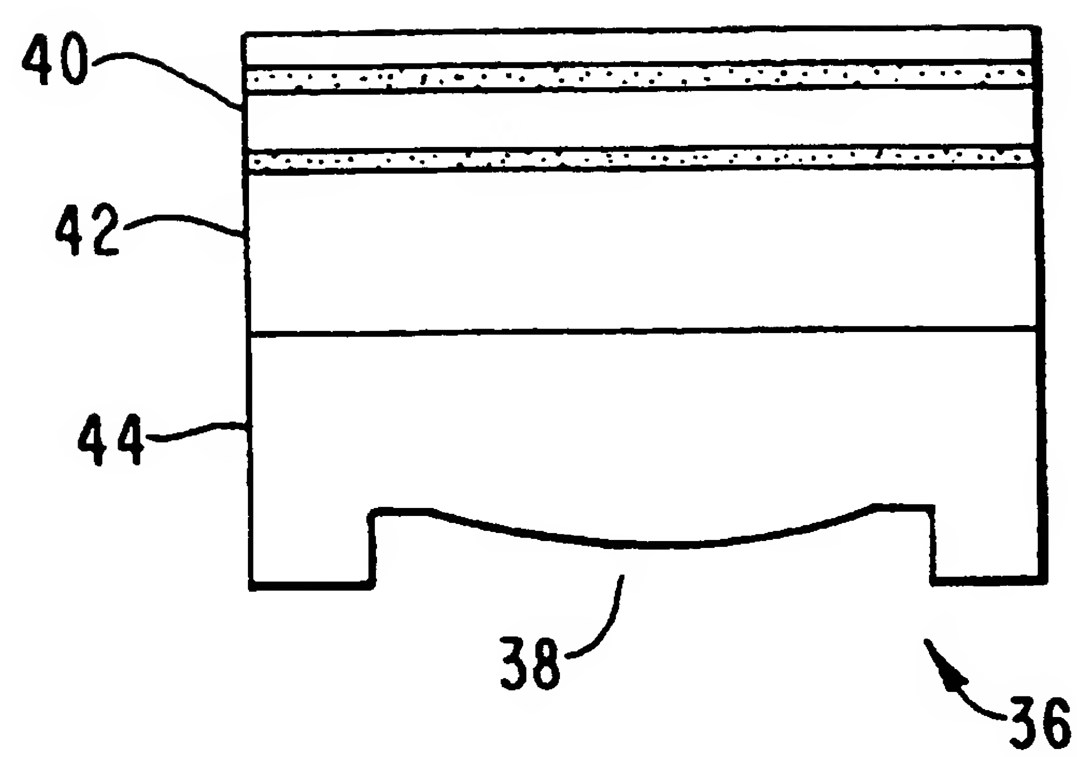


FIG. 3

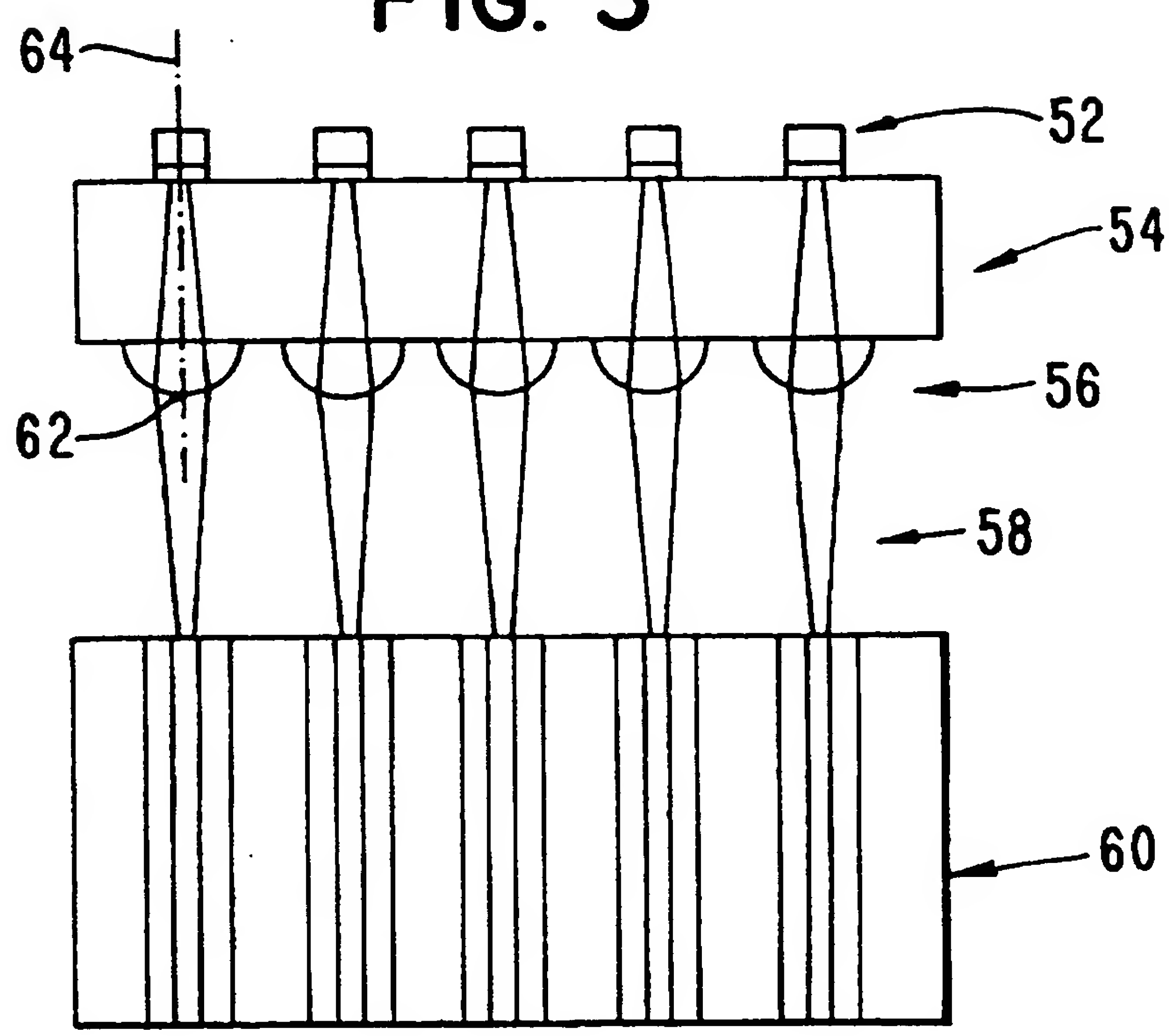
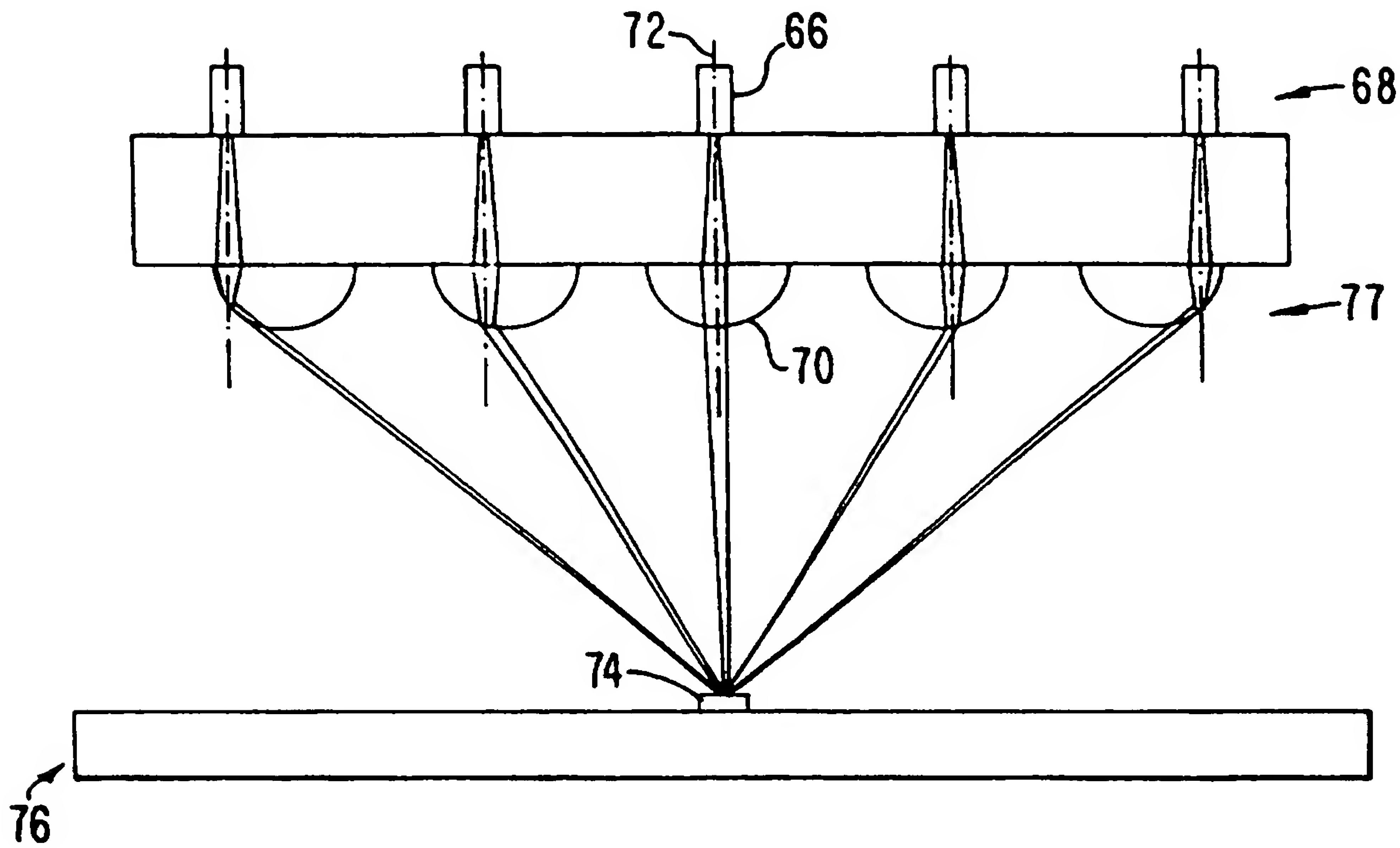


FIG. 4



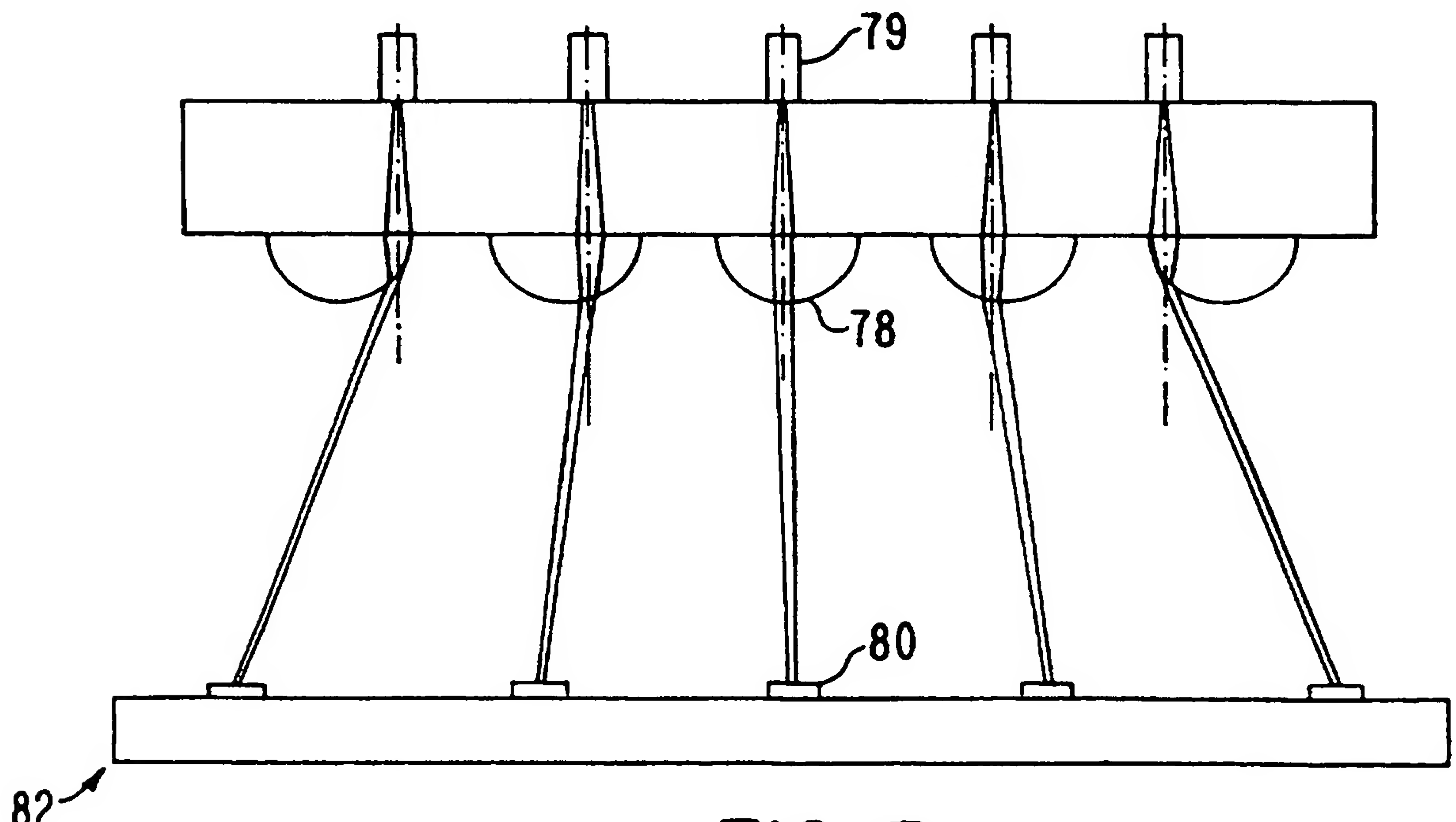


FIG. 5

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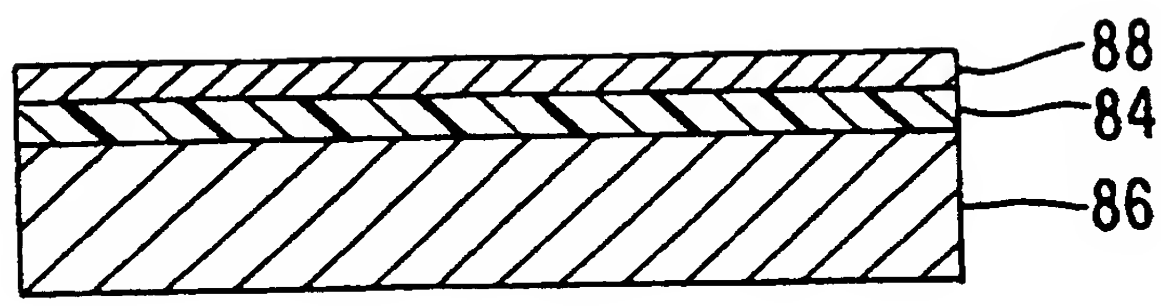


FIG. 6

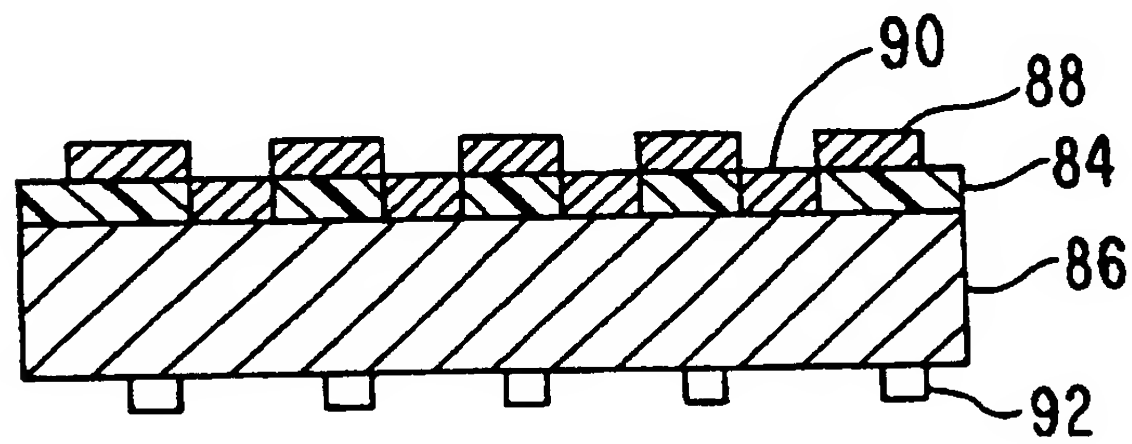


FIG. 7

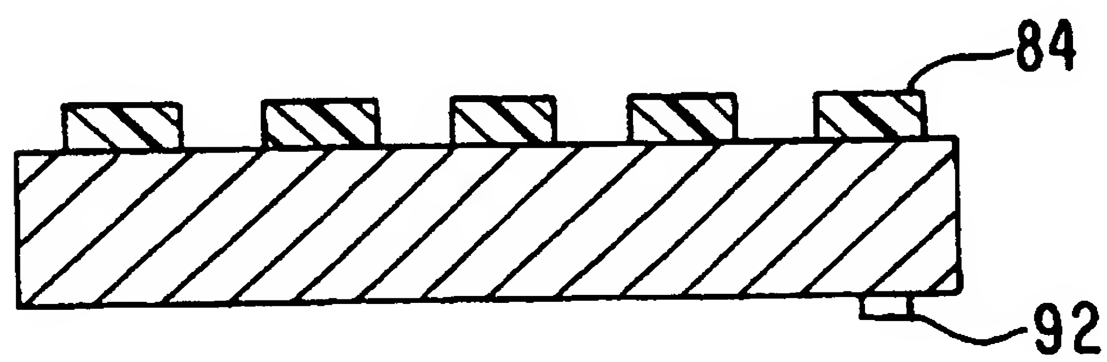


FIG. 8

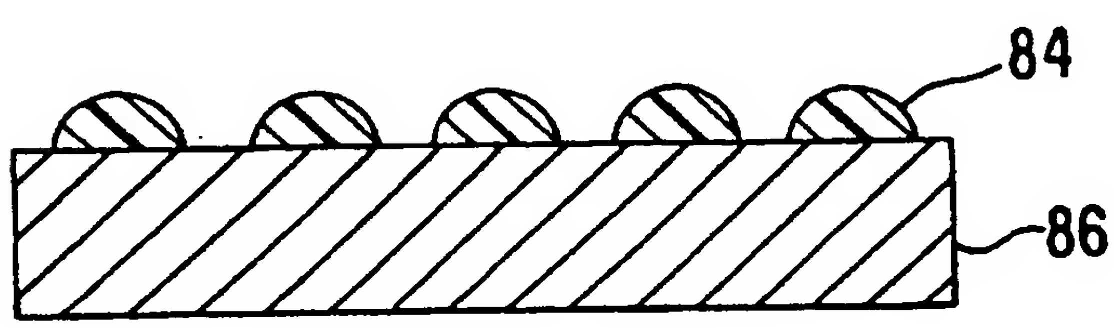


FIG. 12

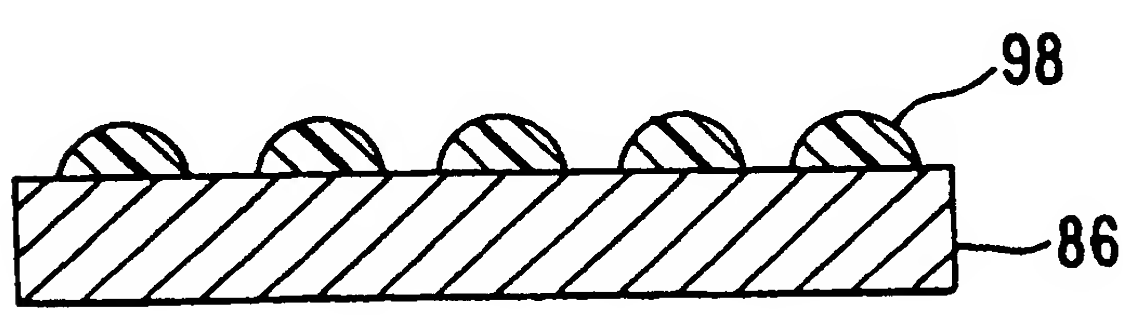


FIG. 13

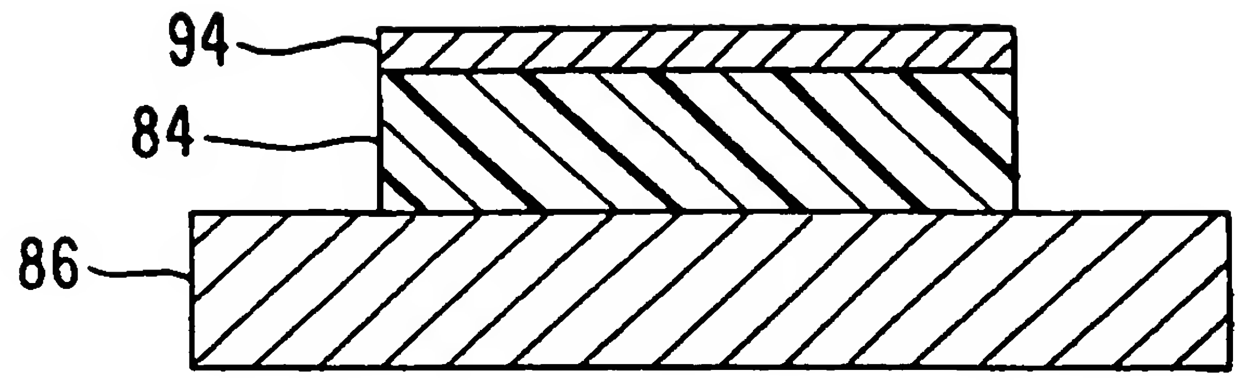


FIG. 9

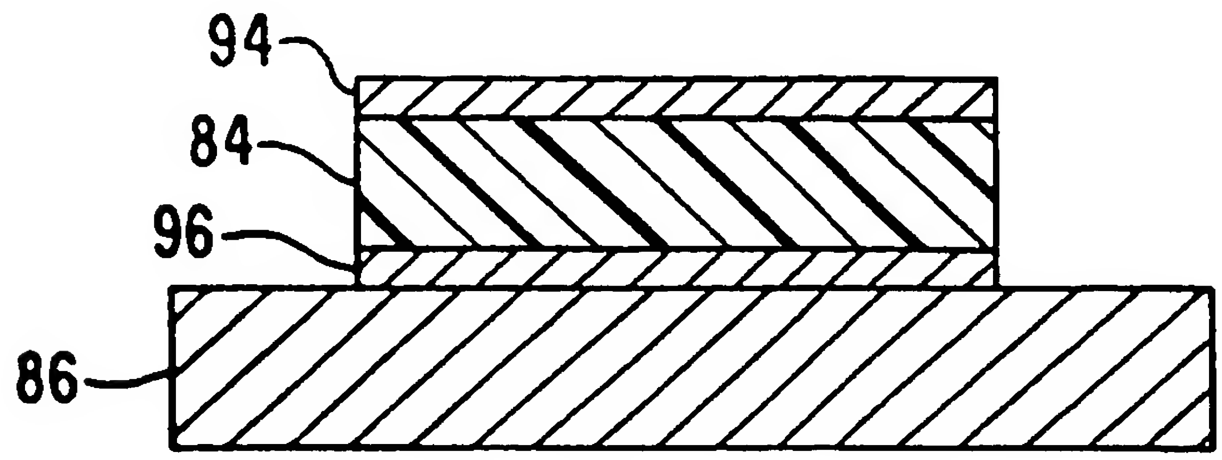


FIG. 10

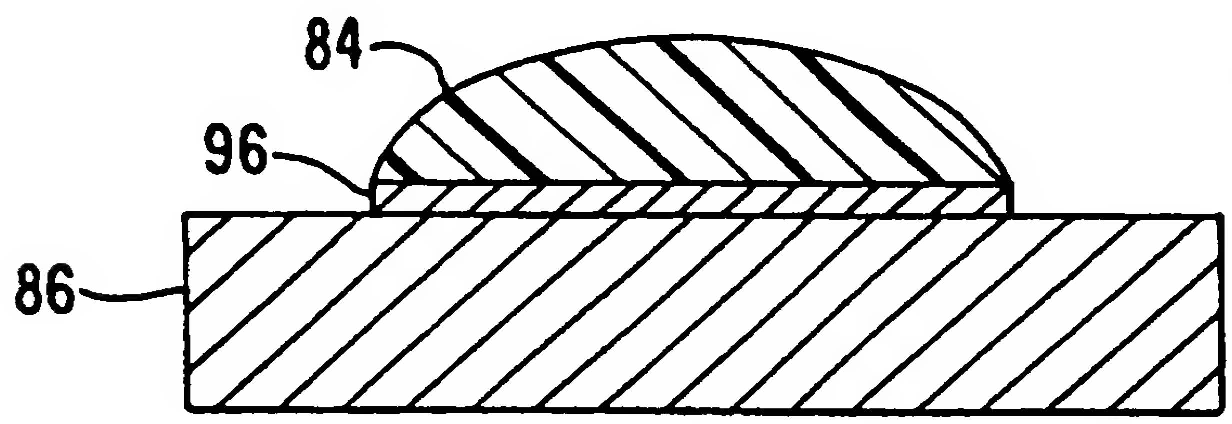
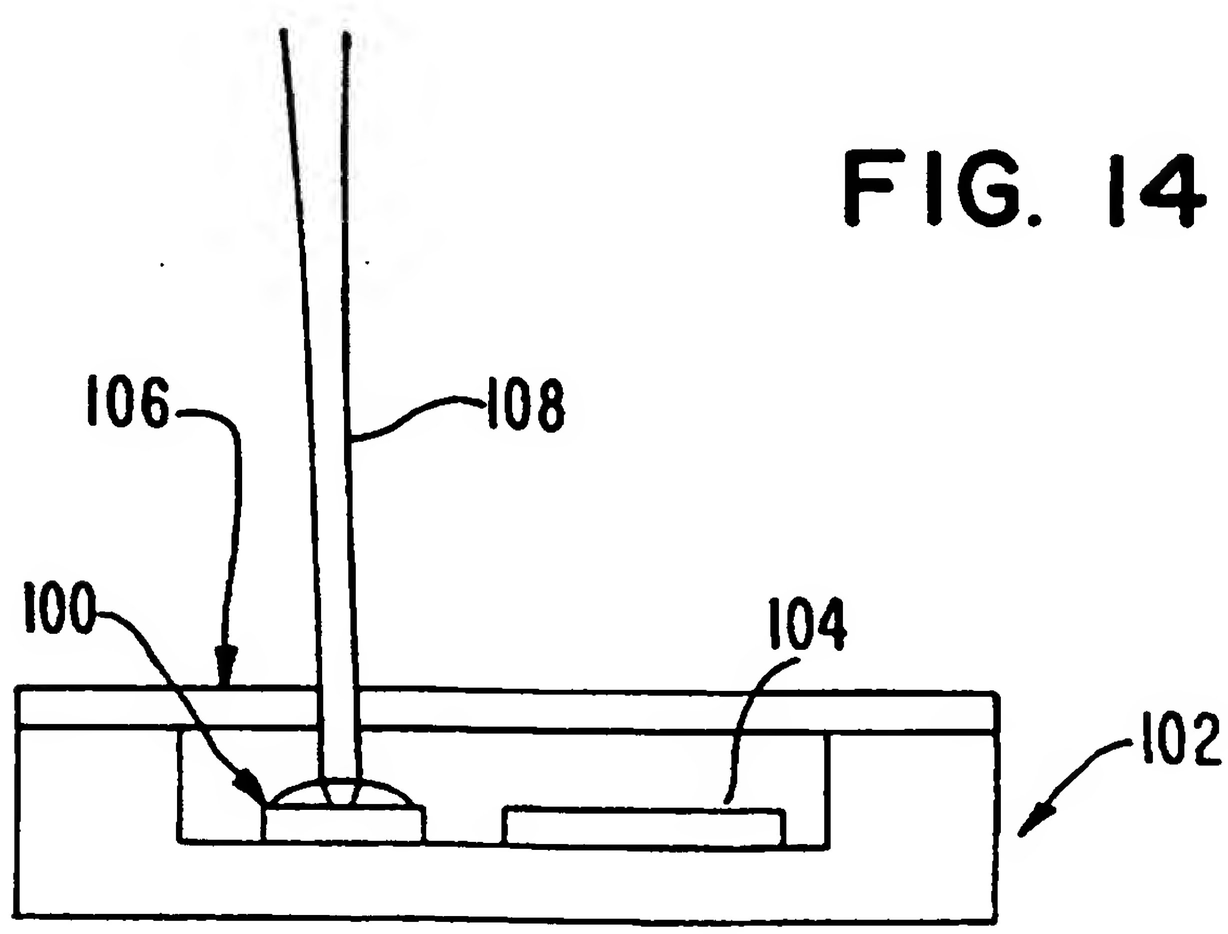


FIG. 11

FIG. 14



INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/06126

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/085 H01S3/25 H01S3/025 H01L33/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ELECTRONICS LETTERS, vol. 31, no. 9, 27 April 1995, page 724/725 XP000517789 STRZELECKA E M ET AL: "MONOLITHIC INTEGRATION OF VERTICAL-CAVITY LASER DIODES WITH REFRACTIVE GAAS MICROLENSES"	1,2,4,5, 7-14,17, 18
Y	see the whole document	3,4,6,15

Y	CLEO'95, SUMMARIES OF PAPERS PRESENTED AT THE CONFERENCE ON LASERS AND ELECTRO-OPTICS, BALITIMORE, MA, USA, 22-26 MAY 1995 (IEEE CAT.NO. 95CH35800), pages 195-196, XP002035656 DU ET AL: "DIRECTIONAL BEAM CONTROL USING ON7OFF-AXIS HIGH EFFICIENCY DIFFRACTIVE OPTICS INTEGTRATED ON SUBSTRATE EMITTING VERTICAL CAVITY LASERS " see the whole document	1,3

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

3

Date of the actual completion of the international search	Date of mailing of the international search report
30 July 1997	28. 08. 97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax (+ 31-70) 340-3016	Gnugesser, H

INTERNATIONAL SEARCH REPORT

Inte. ial Application No
PCT/US 97/06126

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	EP 0 514 283 A (FUJITSU LTD) 19 November 1992 see column 6, line 17 - column 10, line 6; figures 4-6,8-10 ---	1,4,7,8 13
Y	IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 3, no. 9, 1 September 1991, pages 776-778, XP000225787 STEGMULLER B ET AL: "SURFACE EMITTING INGAASP/INP DISTRIBUTED FEEDBACK LASER DIODE AT 1.53 UM WITH MONOLITHIC INTEGRATED MICROLENS" see the whole document ---	1,4,13
Y	PATENT ABSTRACTS OF JAPAN vol. 018, no. 152 (E-1523), 14 March 1994 & JP 05 328233 A (HITACHI LTD;OTHERS: 01), 10 December 1993, see abstract ---	1,3
X Y	ELECTRONICS LETTERS, vol. 31, no. 1, 5 January 1995, page 44/45 XP000504157 BLUM O ET AL: "VERTICAL-CAVITY SURFACE-EMITTING LASERS WITH INTEGRATED REFRACTIVE MICROLENSES" see the whole document ---	1,2,9 1,6,15
X Y	OPTOELECTRONIC PACKAGING (CONF.), SAN JOSE, CA, USA, 1-2 FEB. 1996 (PROCEEDINGS OF THE SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING, , vol. SPIE 2691, pages 43-53, XP002035657 STRZELECKA ET AL. : "MONOLITHIC INTEGRATION OF REFRACTIVE LENSES WITH VERTICAL CAVITY LASERS AND DTECTORS FOR OPTICAL INTERCONNECTIONS " see page 47 - page 50; figures 6,8 ---	1,7-15, 17,18 1,6
A	PATENT ABSTRACTS OF JAPAN vol. 014, no. 156 (E-0908), 26 March 1990 & JP 02 014583 A (MITSUBISHI ELECTRIC CORP), 18 January 1990, see abstract ---	4,13
A	APPLIED OPTICS, vol. 27, no. 7, 1 April 1988, pages 1281-1284, XP000118684 POPOVIC Z D ET AL: "TECHNIQUE FOR MONOLITHIC FABRICATION OF MICROLENS ARRAYS" see the whole document ---	1-18

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	J. ELECTROCHEM. SOC.: SOLID-STATE SCIENCE AND TECHNOLOGY, vol. 131, no. 10, October 1984, pages 2373-2380, XP002035658 WADA : "ION-BEAM ETCHING OF INP AND ITS APPLICATION TO THE FABRICATION OF HIGH RADIANCE INGAASP/INP LIGHT EMITTING DIODES" see the whole document -----	1-18

3

BNSDOCID: <WO 9740558A1 IA>

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 97/06126

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 19 - 25
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
Claim 19 (part 2) and claims 20 - 23 missing from file.

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 97/06126

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0514283 A	19-11-92	JP 5055703 A	05-03-93
		DE 69201908 D	11-05-95
		DE 69201908 T	03-08-95
		US 5309468 A	03-05-94

Form PCT/ISA/210 (patent family annex) (July 1992)

BNSDOCID: <WO_________9740558A1_IA>